Development of a Novel Robotically Effected Plastic Foam Sculpting System for Rapid Prototyping and Manufacturing

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ABSTRACT

This thesis presents the development of a novel robotically effected plastic foam sculpting system for rapid prototyping and manufacturing purposes. The developed system is capable of rapidly sculpting physical objects out of expanded and extruded polystyrene using an electrically heated Nichrome sculpting tool.

An overview of current conventional rapid prototyping systems indicated that the main disadvantages lie in the limited size of objects which can be built, the relatively long time involved to produce one part and the high cost of the systems and materials. An extensive literature and technology review was conducted on work which was similar to the novel system presented in this thesis. The literature provided many good ideas which could be applied.

Two sections of experimental work were conducted. The first was aimed at simply proving the concept of robotically effected sculpting of plastic foams. A crude procedure was developed which proved to be rather tedious and manual, especially in terms of generating the tool paths. Qualitative observations of the cut surfaces were used to change the testing parameters to explore their effects and discover which parameters produced accurate and smooth sculpted surfaces. 12 tests were documented and proved that the sculpting of satisfactory surfaces was achievable. The second section of experimental work involved developing the aforementioned crude procedure to make it more automated, especially in terms of the tool path generation and optimisation step. An innovative five step procedure was developed which if followed can produce accurately sculpted artefacts using CAD models of the artefacts as the primary input. Two artefacts were successfully sculpted using the developed procedure. The first was a simple lofted surface; the CAD model of which was created in SolidWorks. The second artefact was a patient customised medical radiation therapy head and neck support; the CAD model of which was created by scanning the back of the author's head and neck with a 3D scanner. The sculpted support fitted the author perfectly. The implementation of the procedure in the two tests highlighted several points including the speed in which the whole process can be carried out. The time taken from the scanning of the authors head and neck with the 3D scanner through to the physical sculpted artefact, was a mere 80 minutes; of which only 13 minutes was consumed in the actual setup and sculpting step! This is extremely quick when compared to conventional rapid prototyping systems and CNC milling.

Several areas of future work were outlined and included, tool and fixture design, automation and integration of the system procedure, tool pathing strategy for foam cutting and robot control system issues.

The work presented in this thesis provides an excellent foundation for future development of the robotic foam sculpting system.

ACKNOWLEDGMENTS

This project has provided an excellent learning experience and has resulted in the development of an exciting new rapid prototyping and manufacturing technology. Supervision from Dr. Malcolm Taylor and Dr. David Aitchison has been much appreciated and most helpful. Additionally, my colleague Hadley Brooks, who has been working on another aspect of the project, provided invaluable assistance and advice throughout the project.

Scott Amies, Eric Cox, Ken Brown, Paul Wells and Julian Murphy also deserve mention for their help with sourcing equipment and fabrication of components.

Finally I would like to thank my wife Michelle for her dedicated love and support throughout the project.

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ABBREVIATIONS

The following abbreviations are used throughout this thesis for convenience.

Abbreviation	Definition as used in thesis
.STL	Stereolithography (file format)
.TXT	Text (file format)
2D	Two Dimensional
3D	Three Dimensional
CAD	Computer Aided Design
CAM	Computer Aided Manufacturing
DoF	Degrees of Freedom
EPS	Expanded Polystyrene
FDM	Fused Deposition Modelling
IGES	Initial Graphics Exchange Specification
LENS	Laser Engineered Net Shapping
LOM	Laminated Object Manufacturing
NURBS	Non-rational Uniform B-Spline
PC	Personal Computer
RP	Rapid Prototyping
RP&M	Rapid Prototyping & Manufacturing
SLM	Selective Laser Melting
SLS	Selective Laser Sintering
TCP	Tool Centre Point
XPS	Extruded Polystyrene

1 INTRODUCTION AND THESIS OBJECTIVES

Rapid prototyping (RP) is a relatively modern term (mid 1980's) which refers to a process whereby physical objects are produced by a RP machine using an additive 'layer by layer' technique. The majority of RP machines create physical models from a computer aided design (CAD) model by depositing the modelling media one cross section at a time from top to bottom (or vice versa) until the complete model is built. The process has replaced the need for manual prototype model building due to its speed and accuracy. RP technologies find themselves being utilised for many applications such as:

- Iterative component design
- Prototypes for fit and tolerance checking
- Prototypes for concept validation
- Prototype tooling for limited run plastic injection moulding
- User customised product design
- Patterns for lost wax casting process
- Production of patient customised surgical implants

The RP market is large and varied which is evident in the variety and range of RP technologies and building materials available. The main disadvantages of conventional RP technologies lie in the limited size of objects which can be built, the generally long time involved to produce one part and the high cost of the systems and materials. Successful RP systems by and large are those that minimise the aforementioned disadvantages.

This thesis therefore proposes a novel rapid prototyping and manufacturing (RP&M) system which is capable of rapidly producing large sized physical objects out of polystyrene. The proposed system utilises a 6-axis articulated robot fitted with an innovative electrically heated nichrome cutting tool which sculpts objects using the CAD model of the object as the primary input to the system. A 6-aixs articulated robot was chosen for its versatility, large working envelope and its ability to move smoothly at speed. Polystyrene was chosen as the modelling media because it is easy to sculpt with heated tools (low cutting forces), lightweight and cost effective. Envisioned applications for the proposed system include:

- Large scale prototype models
- Patterns for the 'lost foam' casting process
- Medical applications such as patient customised moulds and supports
- User customised helmet linings
- Architectural and sculpting applications
- Marine and aeronautical applications

Machines to cut polystyrene are common and have been around since the creation of the material. However, typical conventional machines utilise a taut hot wire cutting tool which greatly restricts the geometry which can be sculpted (e.g. double concave surface geometry is impossible). The proposed system is not limited by such geometry.

The work presented in this thesis was primarily aimed at developing the aforementioned novel RP&M system, which to the author's knowledge is original and had not been attempted before. The work had the following objectives:

1. Conduct background research into conventional RP systems and current/developing systems which are similar to the system proposed in this thesis. Determine their advantages, disadvantages and any useful attributes which could be of use to the proposed system.
2. Prove the concept of 3D robotically effected sculpting of foam plastics with an electrically heated tool, comprising a loop of Nichrome ribbon and using a CAD model as the primary input to the process.
3. Qualitatively assess the surface of any objects sculpted in order to determine the parameters that produce accurate and smooth sculpted surfaces.
4. Develop the process to embody a high level of automation. Of particular importance is the need to automate the generation and optimisation of tool paths and subsequent conversion to the native robot language.
5. Assess the efficacy of the developed process by sculpting an object for a practical application.
6. As a result of achieving the above objectives, recommend critical areas for future work and development.

The thesis is presented in the order of these objectives. Objective 1 is accomplished in section 2 – 'Background Research', objectives 2 – 5 are realised in section 3 – 'Experimental Work', while objective 6 is achieved in section 5 – 'Future Work and Recommendations'.

The project was undertaken at the Mechanical Engineering Department of the University of Canterbury and was proposed by Dr. David Aitchison and Dr. Malcolm Taylor.

2 BACKGROUND RESEARCH

2.1 Introduction

The system which is developed in this thesis is essentially a cross between a conventional polystyrene cutting machine and a flexible rapid prototyping machine. It was therefore necessary to conduct two distinct areas of background research in conventional 'additive rapid prototyping' and 'current or developing systems which are similar to the proposed system'.

The background research on additive rapid prototyping covers the basic principles of additive rapid prototyping and provides an overview of the main competing systems along with their respective advantages and disadvantages. This is followed with a summary which also briefly discusses several favourable attributes which could be emulated in the proposed system.

The background research on current or developing systems which are similar to the proposed system is essentially a literature and technology review. This section covers both published research and commercialised systems which are similar to the proposed system in at least one of the following four ways:

- Uses an articulated robot for material removal
- Uses extruded or expanded polystyrene for object material
- Uses an electrically heated tool (e.g. hotwire cutter)
- Process is partially or fully automated from CAD model through to finished object

The review is subsequently followed by a summary which includes a list of ideas gathered which could prove useful if applied to the system proposed in this thesis.

2.2 Additive Rapid Prototyping

Additive rapid prototyping (RP) is a process in which three-dimensional physical models are fabricated in a layer-by-layer manner directly from a Computer Aided Design (CAD) model. The range of RP systems along with the materials that can be used in the process are increasing rapidly. Since 1992 more than 7000 rapid prototyping machines have come into use (1). Common build materials are ABS plastic, polycarbonate, wax, paper, metallic powders and elastomers. RP offers the advantage of being able to build parts with complex geometry, which can be impossible to achieve by conventional machining processes. It also allows patterns and dies for net-shape manufacturing processes such as casting and plastic injection moulding to be fabricated cheaply and quickly.

This section covers the RP cycle, and outlines several RP processes and discusses their various advantages and disadvantages.

2.2.1 The Rapid Prototyping Cycle

The following steps are generally followed when a part is to be built by a RP process (2).

1. The object to be built is either modelled in a solid modelling CAD package or 'scanned in' using a 3D scanner and associated software. The CAD model represents an exact virtual model of the object to be built.

The CAD model is then saved as a file native to the CAD system being operated. This file is then exported as a .STL file (**ST**ereo**L**ithography) through built in translators which are used in most CAD packages. A .STL file is a triangulated representation of the solid CAD model. The individual triangles which make up the surface of the model are represented by x, y, z coordinates and facet normal vectors in a text file. Figure 2.2-1 shows a solid part and its .STL representation respectively. Figure 2.2-2 shows a portion of the ASCII text file for the solid part.

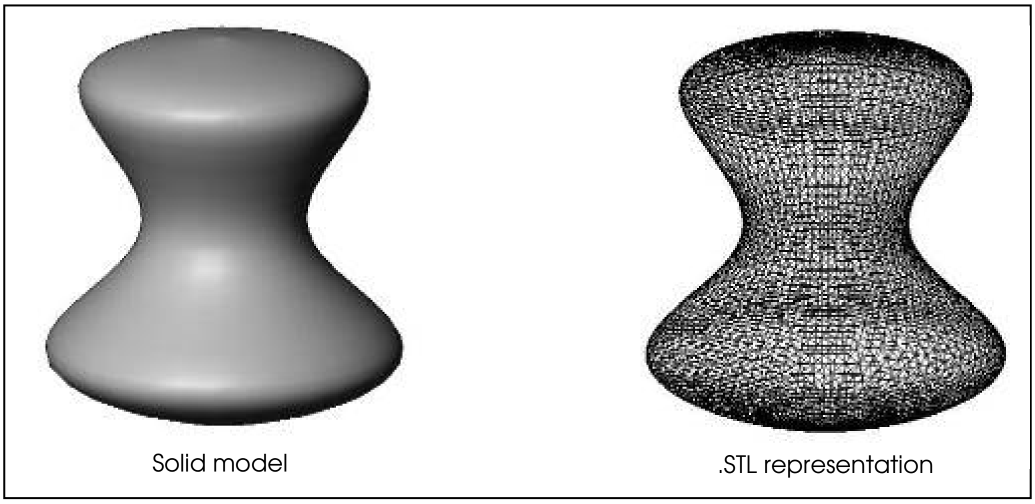


Figure 2.2-1 - Solid model and its .STL representation

```
solid part
  facet normal -2.366929e-001 -9.696507e-001 -6.127021e-002
    outer loop
      vertex 5.673003e+001 3.225216e+000 6.556478e+001
      vertex 6.923723e+001 3.352804e-016 6.923723e+001
      vertex 5.643757e+001 3.225216e+000 6.677029e+001
    endloop
  endfacet
  facet normal -2.440110e-001 -9.696507e-001 -1.536854e-002
    outer loop
      vertex 5.620201e+001 3.225216e+000 6.923723e+001
      vertex 5.626104e+001 3.225216e+000 6.799815e+001
      vertex 6.923723e+001 3.352804e-016 6.923722e+001
    endloop
  endfacet
```

Figure 2.2-2 - Portion of .STL file opened as an ASCII text file

As can be seen from figure 2.2-2, the file consists of blocks containing four lines of code (excluding the loop statements and start/end commands). Each block represents a triangular facet. The first line in the block gives the normal vector for the facet. The next three lines give the x, y and z coordinates for each of the three vertices of the facet.

It is very important that the .STL file contains enough facets to define the detail of the object. The object, when built, will look exactly like the .STL file, which means, if too few facets are used, the object will exhibit flat faceted surfaces as opposed to smoothed surfaces. The user can control the faceting level at the export stage. The .STL representation of the object in figure 2.2-1 contains approximately 7000 facets and is 100 mm x 40 mm x 40 mm in size.

2. Once the .STL file has been created, it must be pre-processed prior to being 'read in' by a RP machine. Each RP system has its own pre-processing requirements. Some RP systems can read in the raw unprocessed .STL files while most require operations such as verification, slicing and setting of control parameters for the machine. 'Slicing' generates a collection of sequential cross-sections of the model, which are separated by a small distance (the distance depends on the RP machine). The slicing process is performed by a simple mathematical algorithm, which finds the intersection points of the slicing plane and the triangular facets (3) which are described by the data in the .STL file. These cross-sections are saved into a file specific to the RP machine being used.
3. Once the file has been generated it can be transferred to the RP machine. The RP machine builds up the model layer by layer based upon the cross-sections in the file. The build process can take as short as a few hours to as long as a few days depending on the process and the size of the part being built.
4. The final step is post-processing. This step requires, removing the part from the machine, removal of any supporting material and finishing (sanding, painting etc.). It should be noted that some processes produce a surface that does not require finishing (e.g. EnvisionTech system as discussed in section 2.2.4)

2.2.2 Fused Deposition Modelling (FDM) (2)

FDM is one of the main RP processes used today. The FDM system uses an extrusion head which deposits material layer by layer. The extrusion head is the critical part of the whole system. It works by pushing polymer filament into a heated chamber just before the nozzle where it is melted and extruded onto the growing model. The nozzle's opening diameter is only 0.3 mm. During extrusion, the nozzle is close enough to the model to act as a shearing/smoothing device, which produces a flat surface ready for the next layer to be deposited. A secondary nozzle is also used to deposit support material (a different material to the build material) in the same manner as the main nozzle. Once a layer has been completed, the table that supports the object is lowered by the thickness of one layer (current minimum of 0.178 mm (4)) and the next layer can be deposited. This cycle is repeated until the object is built. The latest innovation by Stratasys Inc, is a water soluble support material which can be washed away once the model has been built which allows even more complex geometry to be built. Figure 2.2-3 shows a medium sized FDM machine and some typical components produced by it. FDM is generally used to prototype parts to verify aspects such as fit due to the excellent strength properties of the build materials. Common FDM build materials used are ABS plastic, polycarbonate and wax.

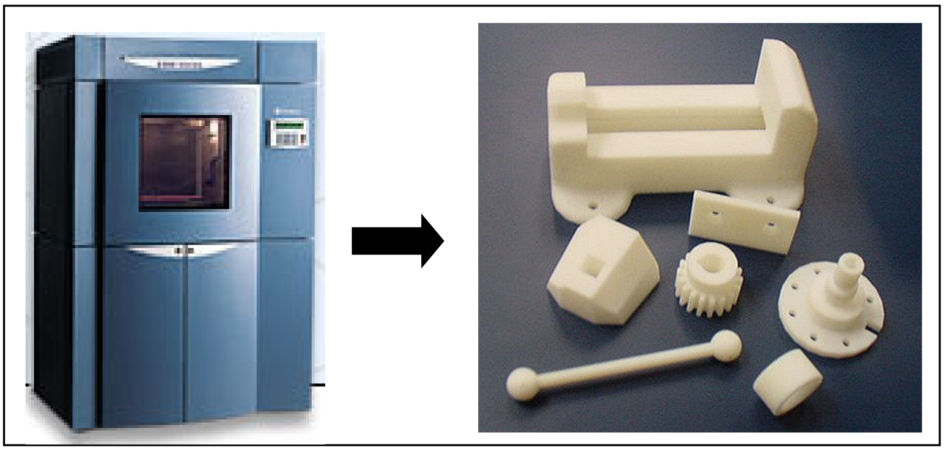


Figure 2.2-3 - FDM machine and produced parts

<u>Advantages</u>

- Build materials exhibit excellent strength and temperature properties
- Capable of creating wax patterns for investment casting
- Relatively simple mechanical systems
- Simple post-processing especially with water soluble support structures

<u>Disadvantages</u>

- Slower build times than laser based systems
- High system cost
- Thin column type details are hard to achieve because the physical contact with the nozzle can topple or shift the structure
- Stepped surface finish

2.2.3 Laminated Object Manufacturing (LOM) (2, 5)

This RP system utilises the inexpensive build material of paper to build complex 3D models layer by layer. LOM is one of the fastest RP processes around and is capable of producing parts up to 20″ x 30″ x 24″. LOM works by laser cutting 2D cross-sections out of adhesive coated paper which are then laminated together with the help of a hot roller. Figure 2.2-4 shows a schematic of the LOM process.

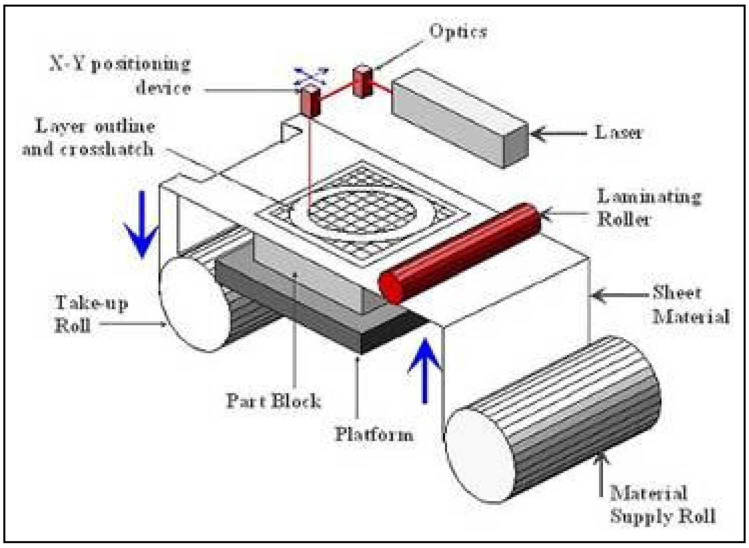


Figure 2.2-4 - The LOM process (5)

The LOM build sequence is as follows:

1. A foam pad (not shown in figure 2.2-4) is mounted to the platform to secure the object and ensure ease of part removal.
2. The .STL file is read into the machine and the sliced cross-sections are generated while the object gets built. This is unlike most systems which generate all the cross-sections prior to building.
3. The paper is fed over the foam pad (or previous layer for subsequent cycles). The heated roller makes two passes over the paper to bond it to the pad (or previous layer for subsequent cycles).
4. The laser cuts out the cross-section and also cuts a cross hatch pattern in the waste material to aid subsequent removal. A bounding perimeter is also laser cut, which acts to contain the part and waste material. The laser is capable of exactly cutting through one layer of paper, which is generally around 0.125 mm thick.
5. The platform is then lowered and the next layer of paper is fed on.
6. Once the part has been built, it is separated from the foam pad and the bounding box is removed. The waste material is then removed through a process known as 'de-cubing' and can be rather time consuming especially if the object's geometry is complex/delicate.
7. The part can then be coated with a primer to seal it from moisture and then painted.

LOM machines are typically used to generate concept verification models. They allow designers and engineers to visually check the concept before investing in expensive tooling. The models generated by LOM are relatively robust but should not be used for 'fit' checks. Figure 2.2-5 shows a typical LOM machine and a part produced by it.

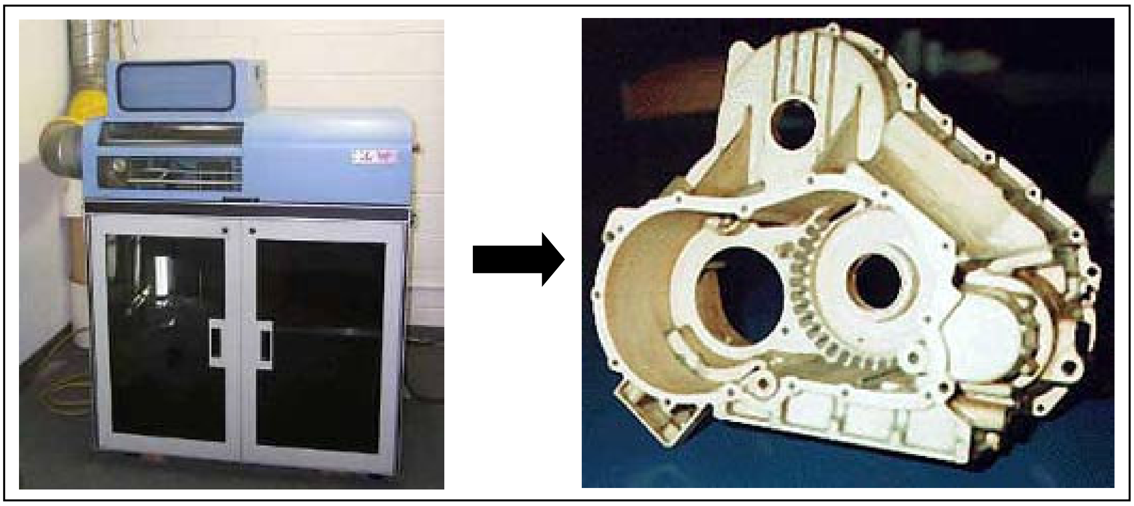


Figure 2.2-5 - A typical LOM machine and part produced by it

Advantages

- Fast build time
- Inexpensive build materials
- Simple system operation
- Good dimensional accuracy possible
- Can be used to make the negative for investment casting wax pattern injection
- Suitable for sand casting patterns
- Large parts can be built (up to 30")
- Little pre-processing required

Disadvantages

- A substantial ventilation system is needed because the process uses a laser to burn/cut paper and adhesive
- De-cubing process is sometimes time consuming
- Parts can only effectively be used for concept verification

2.2.4 Photopolymerisation by EnvisionTech (6)

EnvisionTech is a German company which produces a RP system called the Perfactory. The Perfactory system works by selectively curing liquid resin cross-sections layer by layer. Unlike stereolithography systems, which cure the resin by tracing the cross-sections with a laser, the Perfactory cures the whole cross-section in one flash of visible light through a mask. This makes the process a lot quicker than stereolithography systems. The Perfactory comes in two models, which vary in size; the 'Standard' and the 'Mini'. The Mini is aimed at applications such as jewellery. The 'Mini' is capable of 25 micron resolution. The Perfactory build sequence is as follows:

1. One of the following data files are fed into the operating PC: .STL file, data cloud from 3D scanner or CT/MRI data files from medical scanning.
2. The files are converted into negative bitmap images of the cross-sections which comprise the object.
3. The negative bitmap images are transferred to the RP machine. The image representing the top cross-section of the model is projected through a glass screen from below which is immersed in liquid resin and is positioned just below the surface of the resin. The liquid resin, which is exposed to the light through the negative bitmap image, is cured. The projecting system works similar to that of a data projector but possesses a higher level of resolution.
4. The cured layer is then attached to a device, which raises it vertically by one layer thickness. The cured section is still immersed in the liquid resin but is supported at a distance of one layer thickness off the glass plate.
5. The next negative bitmap image is projected and the liquid resin between the cured layer/s and the glass is cured. The process is repeated until the complete model is built.

Figure 2.2-6 below shows the Perfactory 'Standard' system and some components produced by it.

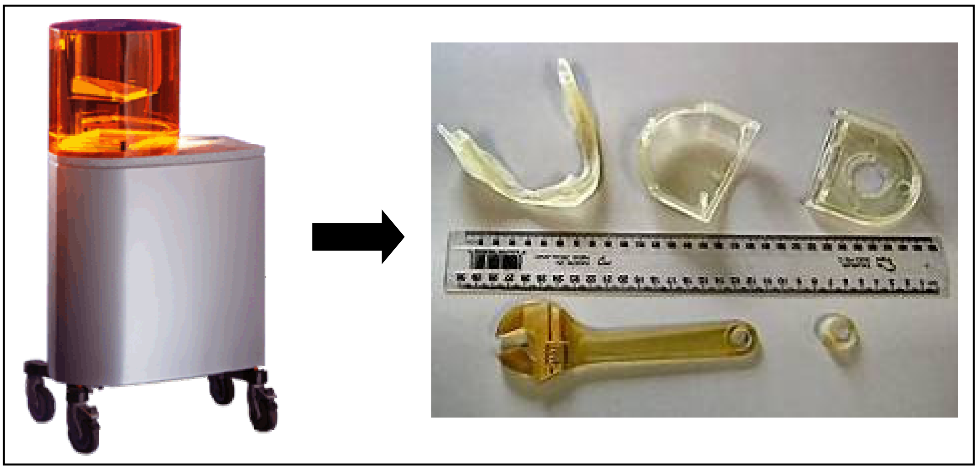


Figure 2.2-6 - Perfactory system by EnvisionTech and typical parts produced by it

The EnvisionTech system is compatible with several materials. The main material which is used is an orange coloured Methacrylate which is a thermoset. The hardness of the finished model can be varied by altering the intensity of the projected light. This allows the creation of fully flexible models. Another common material is a neutral skin coloured material, which can be used to produce custom fit hearing aids and the like. There are also several other materials which can be used successfully for investment casting wax patterns. The EnvisionTech system produces surface finishes superior to stereolithography (previous industry benchmark).

Advantages

- Low-cost system compared with others which produce similar quality parts
- Fast build time
- Models can be used for concept verification and fit analysis
- No lasers or jets, just visible light
- Clean and compact
- Parts can be used for investment casting

Disadvantages

- Only relatively small models can be built
- Resin must be carefully stored so it does not cure
- Uses same material for support, which is snapped off once the object is built. This ruins the surface finish in that area, which must be sanded manually.

2.2.5 Selective Laser Sintering (SLS) (2, 7)

SLS is one of the oldest RP systems, which has grown through many years of development. The process works by sintering powder, layer by layer with a powerful CO_2 scanning laser. The layer thickness can be as thin as 0.08 mm which provides excellent surface resolution. Figure 2.2-7 below describes the build process.

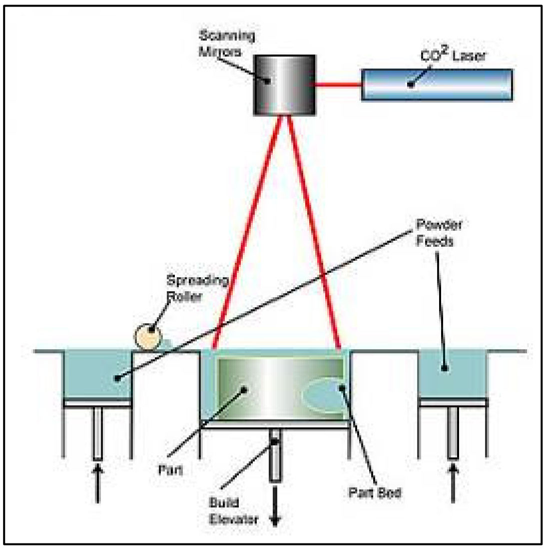


Figure 2.2-7 - The SLS build process (7)

As can be seen from figure 2.2-7, the part is supported on a piston which is lowered layer by layer. Once the scanning laser has sintered a cross-section, the piston lowers by one layer thickness, more powder is distributed on top by the spreading roller and the next cross-section is sintered. The process is repeated until the part is built. Once the part has been built, it is removed from the machine encapsulated in a powder cake. The powder, which encapsulates the part, acts as the support structure, which can be filtered and re-used. Post-processing of the part is required, which involves removing the object from the powder cake using brushes and hobby picks. Depending on the material used the part will also require glass bead grit blasting to improve the surface finish. This must be carried out in a special facility provided as a peripheral with the SLS system. Due to the nature of the build process it is possible to nest as many objects into the build envelope as possible. This can be done in three dimensions as opposed to most systems, which require all objects to start on the same level (i.e. 2D nesting only). The laser is capable of scanning large parts within seconds making the process extremely fast when the entire build envelope is filled with parts. The SLS system uses the typical .STL file to generate cross-sections.

The most common commercial SLS system is known as the 'Sinterstation' and comes in various sizes. The Sinterstation has a vast range of materials which can be used. The materials are grouped into three modules based on the applications of the final object. These modules are 'casting', 'functional prototypes' and 'rapid tooling'. The casting module contains materials such as polycarbonate and sand casting sands, which can be used, for investment casting and sand casting respectively. The functional prototype module contains materials such as glass-filled Nylon and thermoplastic elastomer. The glass-filled Nylon can be used for both concept verification and fit analysis. The thermoplastic elastomer produces rubbery parts with elongation properties of up to 100%. The rapid tooling module contains materials such as 'RapidSteel' and Copper Polyamide. The RapidSteel material is a 1080 carbon steel powder, which can be used to produce injection-moulding dies for limited production runs. The dies must be fired and infiltrated with copper before use, to improve their durability. Copper Polyamide can be used to produce soft tooling without the post-processing time and cost associated with RapidSteel.

Figure 2.2-8 below shows a Sinterstation 2500 and some components produced by it.

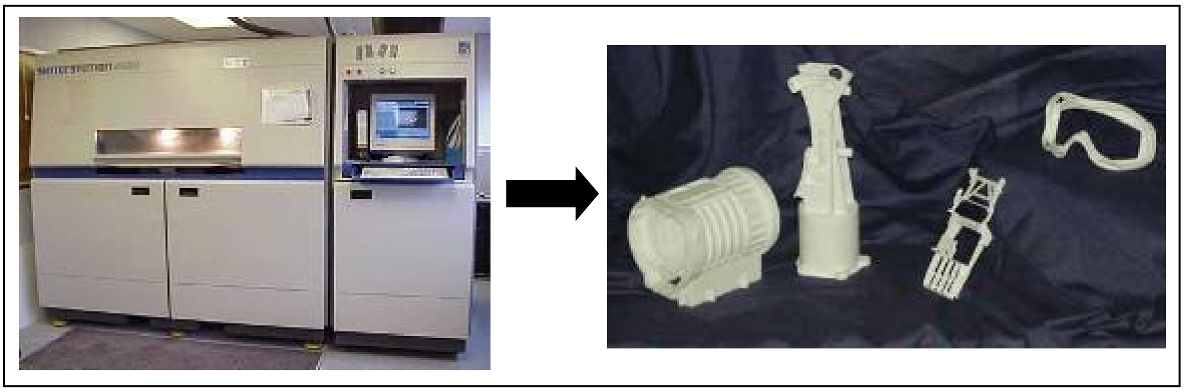


Figure 2.2-8 – Sinterstation and components produced by it

Advantages

- Productive especially when the 3D nesting capability is used
- Huge variety of build materials and applications
- RapidSteel is capable of producing injection moulding dies for limited production runs at a low price
- High dimensional accuracy

Disadvantages

- One of the most expensive and complex systems around
- High maintenance costs
- Not suitable for the office
- Requires peripheral systems such as glass bead grit blasting facility
- Big and heavy (30 ft^2 of floor space required and weighs 2850 kg)

2.2.6 Various Other RP Technologies

The technologies, which are described in sections 2.2.2 – 2.2.5 provide a good cross-section of the many, and largely varying RP technologies available on the market. However, there are several other technologies, which deserve mention.

Stereotithography (2):

Stereolithography was the first RP process to become commercially available on the market in 1987. It was developed and introduced by 3D Systems, Corp., in Valencia, California. The process is very similar to the photopolymerisation method recently developed by EnvisionnTech (see section 1.1.4). The main difference lies in the way the resin is polymerised. The process uses a low powered laser to trace around the cross-sections as opposed to exposing the entire cross-section in one flash with visible light. The system also requires a large photopolymer tank unlike the shallow economical tray used by the EnvisionTech system. The laser cures cross-section after cross-section to slowly build up the model. The key advantages of the system lie in its' ability to produce highly accurate models with intricate detail and excellent surface finish.

Selective Laser Melting (SLM):

SLM is a relatively new variation of SLS (see section 2.2.5). The SLM system has been developed by the RP and RT division of the British company, MCP Group. The main difference between the SLM technology and the older SLS technology is in the materials which can be used and its' ability to generate complex intricate structures. The SLM technology uses extremely fine metallic powders such as medical grade titanium, tool steel and stainless steel. Some of the latest applications SLM is being used for include bodily implants (8, 9) and partial denture frameworks (10). SLM is capable of producing mesh like structures, which are extremely strong yet light and allow bone and tissue in-growth. Figure 2.2-9 below show some parts produced by the SLM process.

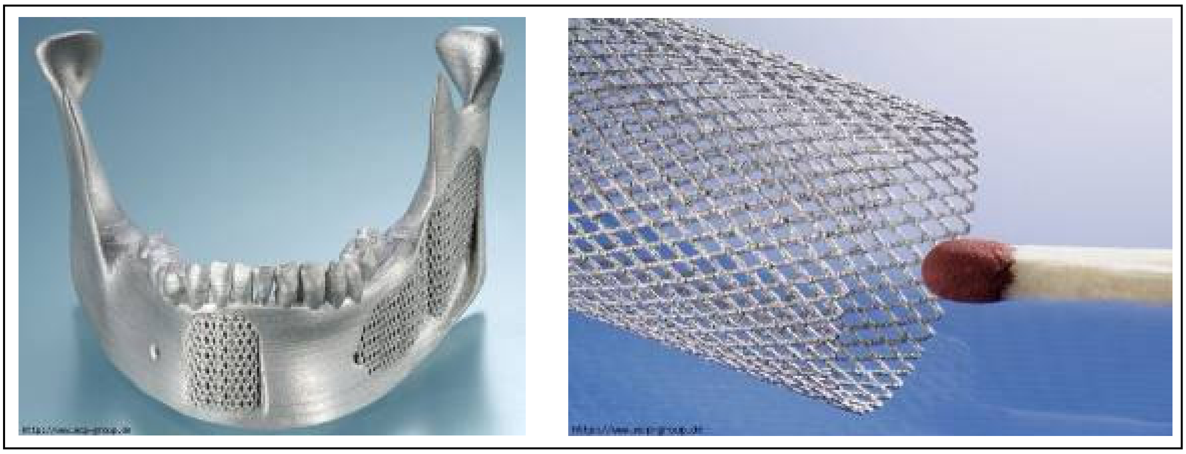


Figure 2.2-9 - Artefacts produced by SLM

Laser Engineered Net Shaping (LENS) (2, 11):

LENS has been touted as the first "true" direct-metal RP system, in that parts produced by the process are full strength metals upon removal from the machine. The LENS system was developed by Sandia National Laboratories, USA and is manufactured and sold by Optomec Design Company in Albuquerque, NM, USA. The process works by feeding fine metal powder through four feeder tubes into the focal point of a 700 W Nd Yag laser. The material is effectively welded in place layer by layer. The LENS process is capable of producing extremely thin strong sections. Parts produced by LENS can be used directly like any other metal components. There are also possibilities that the LENS process could be used to produce cost-effective, strong rapid tooling. Figure 2.2-10 below shows some components produced by the LENS process.

Figure 2.2-10 - Components produced by the LENS process

Objet (12):

The Objet system is one of the newest systems on the market. It has been developed and produced by Objet, a company that was founded in Rehovot, Israel in 1998. The Objet system is essentially a 3D printer capable of printing complex 3D objects using polymer materials. The Objet system contains thousands of jets (as opposed to FDM which only has two jets. See section 2.2.2), which deposit polymer material layer by layer. They boast extremely fast build speeds and superior surface finish and accuracy. They use a gel like support material that can be easily removed by hand or with water once the object has been built. The Objet systems are also capable of producing parts with sections as thin as 0.6 mm. Objet are renowned for producing systems that are exceptionally office/user friendly. Figure 2.2-11 below shows the Objet Eden 500V system and a part produced by it.

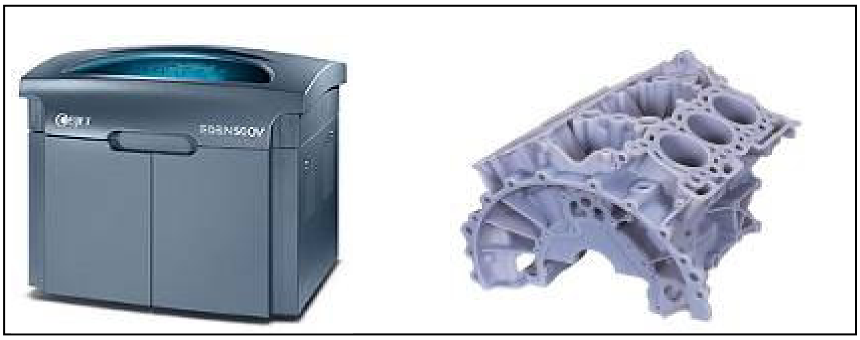


Figure 2.2-11 - The Objet Eden 500V and a component produced by it (not to scale)

2.2.7 Additive RP Summary

All additive RP processes are based on a layer by layer building process. All systems use the .STL file format, which is a triangulated representation of the surface of the solid model. The file is essentially a text file with x y and z coordinates for the vertices of each triangular facet. The triangulated representation is sliced from top to bottom (or vice-versa) using a mathematical algorithm to generate a collection of sequential cross-sections separated by a small distance (the distance depends on the process). The collection of cross-sections is then used to build the model up, layer by layer.

The majority of RP machines require little user experience, and are capable of producing complex parts, which would take a lot longer or are impossible to make using conventional subtractive machining methods. The number and variety of materials which can be used by RP machines, are increasing rapidly which is turning RP processes into potential rapid manufacturing and rapid tooling processes.

The major disadvantages of most additive RP systems lie in the following areas:

- Most machines can only produce relatively small components (average build envelope is around 300 x 300 x 300 mm).
- Build times are slow compared to net shape forming processes (e.g. injection moulding). The number of layers and their thickness are the main limits to build time. To achieve a good surface finish a model must be comprised of a large number of thin layers. The slow build time is a major draw back in using RP technology for mass manufacture of parts.
- Initial system cost is generally high.
- High level of maintenance generally required.
- Build materials are generally provided by the manufacturer of the machine only, which pushes the price up.
- The strength of the produced parts is generally weaker than if they were machined from a blank of the same material.

There are several aspects of additive RP processes, which could prove useful when applied to the proposed subtractive hot-wire foam process. The first of these is the file preparation including the .STL export format and the generation of cross-sections using a mathematical algorithm. For example, the object to be carved out of foam could be modelled, exported in the .STL format and then sliced to generate a series of cross-sections. These cross-sections could then be used to systematically produce cutting paths for a hot wire cutter. The versatility of the .STL file lies in the fact that it is simply a collection of spatial coordinates, which can be easily interrogated. Another aspect is that many RP processes produce parts, which can be used for investment, sand or lost foam casting. The proposed system in this thesis uses plastic foams, which could be used for these casting processes making it a real competitor.

2.3 Current or Developing Systems Similar to the Proposed System

This section is essentially a literature and technology review of current systems or systems under development, which are similar to the proposed hot tool sculpting process in the following four ways:

- Uses an articulated robot for material removal
- Uses extruded (XPS) or expanded polystyrene (EPS) for object material
- Uses an electrically heated tool (e.g. hotwire cutter)
- Process is partially or fully automated from CAD model through to finished object

2.3.1 An 8-axis Robot Based Rough Cutting System for Surface Sculpturing (13)

This paper was submitted by the Tokyo Institute of Technology in Japan. The paper outlines the development of an innovative 8-axis robot based rough cutting system which is capable of quickly sculpting 3D objects from polystyrene. The system is known as 'Michelangelo' and consists of the following subsystems/components:

- 6-axis Motoman-SV3X articulated robot
- 2-axis table to mount the work piece to
- Cutting tool consisting of a tight hotwire end effector with current controller
- CAD model mesh simplification algorithm
- Tool path generation algorithm
- Virtual reality systems simulator
- Systems interface to integrate the above subsystems

The system can sculpt objects from 100 x 100 x 100 mm blocks of polystyrene which are mounted to the two axis table. The following method is used to produce a sculpted artefact from a CAD model:

1. The CAD model is imported into the system in the .STL format. This can be created by a CAD system or produced from the 3D scanning of physical objects. The triangular mesh is simplified to remove redundant/overlapping data and to produce a final model which is a simplification of the original model. The level of simplification can be specified at this stage by the user.

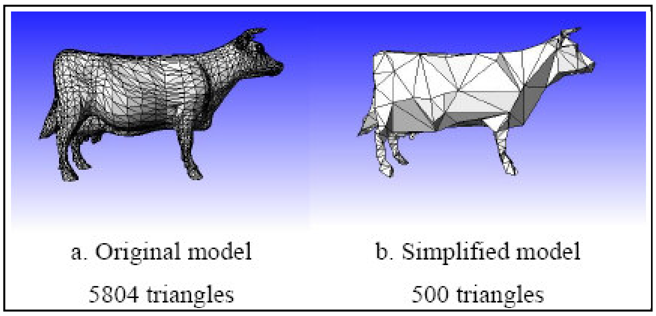


Figure 2.3-1 - Mesh simplification

Figure 2.3-1 shows an example of an original model along with its simplified version. A detailed description of the simplification algorithm can be found in previous work by the authors (14).

2. Once the model to be sculpted has been simplified, a 'rough cutting' set of models is created. This simply offsets the models surface by means of an edge collapse algorithm. A series of offsets are made until the model resembles a cube like object. Each offset model is saved for processing in the next step.

3. The next step creates the paths for the cutting tool to traverse. The work table has two axes (horizontal tilt and vertical twist) which orientate the part so the triangular facet to be cut is presented face-up or face forward. In order to completely cut one facet, the cutting tool need only traverse from one of the vertices to the midpoint of the opposite side. Each of the three possible cutter directions are analysed to find the optimal direction. Each Facet of each offset layer is analysed in this manner.

4. Once the cutter paths have been generated, a virtual reality simulation of the complete setup is run to ensure all paths are traversable by the robot and no collisions or interferences occur.

5. Given the virtual reality simulation was successful the object is sculpted layer by layer, facet by facet from a block of polystyrene.

The authors have conducted several tests to assess the capability and performance of the system. The system proved to work well with simple models and was especially good with convex surfaces. One of the main problems they experienced was with cutting small facets in regions of higher local surface complexity. The poor results stemmed from the fact that when small facets were cut surrounding facets that had already been cut were re-melted due to the tool passing over the top of them. This created an unacceptable surface finish and accuracy. Figure 2.3-2 shows the system and a part sculpted by it.

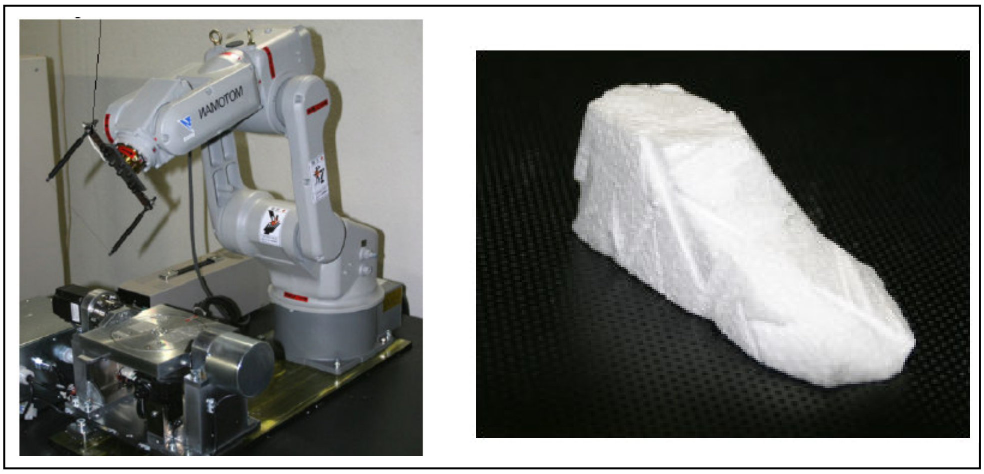


Figure 2.3-2 - The 8-axis setup and a test part sculpted by the system

Advantages

- Fast and effective rough cutting system
- Innovative object simplification and rough offset model generation algorithms
- Virtual reality simulation package for reach-ability and interference analysis
- Effective 2-axis table allows excellent reach-ability

Disadvantages

- Cannot machine concave surfaces or small facets easily
- Cannot machine double concave surfaces at all due to tool limitations
- Tool design limits geometry and size of objects which can be sculpted

2.3.2 Machining Large Complex Shapes Using a 7-DoF Device (15)

This paper was submitted by the Faculty of Design, Engineering and Production at Delft University of Technology in the Netherlands. It outlines a system, which uses a 5-axis articulated robot fitted with a high speed milling cutter. The system is capable of machining large complex shapes out of plastic foams and modelling clays. The stock material is mounted on a horizontal turntable, which can be controlled incrementally via a stepper motor. This allows increased accessibility to complex model geometry. Strictly speaking, the system presented is only a six degree of freedom (6-DoF) system not 7-DoF as stated in the paper title. There are 5-DoF's in the articulated robot and 1-DoF in the turntable which supports the object being machined. The authors consider the rotational axis of the milling cutter as the sixth DoF. Figure 2.3-3 below shows the system in action.

Figure 2.3-3 - The system at work on a model car

The paper was driven by the notion that, optimisation of tool accessibility (i.e. approach direction and angle) would result in fast material removal of complex regions. Five key aims of the research were:

- Obtain smooth surfaces
- Avoid collisions
- Reduce machining time
- Reduce computation
- Automation of machining planning

To achieve smooth surfaces using a milling cutter, they concluded that the tool paths would have to be sufficiently dense in order to eliminate the cusp between adjacent paths.

The authors developed a tool-path generation program from scratch, using a C++ programming package. Tool-path generation was achieved by deriving the optimum tool approach orientations in combination with detecting and avoiding collisions. The optimum tool approach orientations were found by generating a 'light map' and a 'visibility map' (the visibility from infinity of finite regions on the objects surface) for the CAD model. These maps were created by computing the local surface curvature and surface normal of each 'voxel' (essentially a 3D pixel). The detection and avoidance of collisions was achieved by breaking down the system (robot, object and turntable) into collections of spheres of known sizes. This effectively reduced the collision problem to a set of calculations involving the intersection of spheres of known sizes. A computationally expensive aspect of the collision problem was the detection of collisions between the robot linkages and the stock. This was due to the time dependency of the stock volume as it was machined away by the cutter.

Advantages

- Optimised tool approach orientations
- Improved machining efficiency compared to three and four axis machining
- Smooth surface finish with no cusp achieved by 6-DoF control
- Fully automated machining process
- No need to re-fixture object due to controllable turntable

Disadvantages

- Machining process is still relatively slow due to adjacent path spacing of around 1 mm
- Can only machine light plastics
- Not as accurate as conventional CNC machining

2.3.3 Robotic Machining – Programming Plus Inc., Delcam and Kuka Collaboration (16)

Programming Plus Inc. in conjunction with Delcam and Kuka Robotics have recently (2005) launched a revolutionary robotic machining facility. Programming Plus Inc. specialise in producing turn-key CAD/CAM (Computer Aided Manufacturing) and shop-floor automation solutions in collaboration with Delcam and SurfCAM. Delcam is one of the biggest players in the CAD/CAM industry and has produced products such as PowerMill, PowerShape, PowerInspect, ArtCAM, and CopyCAD. Kuka are the German designers and manufacturers of Kuka 6-axis articulated robots.

The facility is capable of machining complex objects out of soft materials such as plastics, foams and the future possibility of aluminium. The facility utilises a 10 kg payload Kuka 6-axis articulated robot, fitted with a high-speed milling cutter as the end-effecter. The stock material to be machined is mounted on a static stand, which is inclined to optimise accessibility. The machining process is similar to that of conventional CNC milling. A roughing sequence is first performed using only 3-axis control with large step sizes. This is followed by a finishing sequence, which uses the full 5-axis control. The machining program was developed using Delcam's existing CAM package, PowerMill. The bulk of the development work involved modifying the program in order to drive a 5-axis articulated device. Like an automated CNC mill, the system is capable of performing fully automated tool changes. Figure 2.3-4 below shows the robotic machining cell and the tool holder.

Figure 2.3-4 - Robotic machining cell and tool holder

Advantages

- Faster than conventional CNC milling
- Complex geometry can be achieved
- Fully automated system
- Accurate to 0.1 mm for large objects
- Excellent for pattern making
- Cost effective
- Less complex than conventional CNC systems

Disadvantages

- Stock fixture is static
- Can only machine soft materials
- Time consuming to achieve smooth surfaces
- Not as accurate as conventional CNC milling

2.3.4 Various Commercial Hotwire Systems

The low cost of foam plastics coupled with their wide range of favourable mechanical, thermal and physical properties has resulted in their rapid proliferation in industry. Tools to cut and shape these materials have existed since the creation of the materials; however it has only been of late that flexible automated multi-axis foam cutting systems have come of age. Such systems typically comprise a taut hotwire (up to lengths of 3 m) which can be traversed through a foam work-piece via motorized carriers at either end which generally possess two degrees of freedom. Most systems incorporate a high level of automation through custom designed software which utilizes simple 2D profile CAD drawings as the primary input. Several systems available also offer additional degrees of freedom via vertical speed controlled turntables or lathe derived spindles to affix the work piece to. It was also observed that several manufacturers also offer profiled tools as opposed to taut hotwires. These tools are inherently less sturdy and as a result cutting speeds must be reduced. However, the geometry obtainable when supplemented by a full complement of motion axes can be of substantial complexity. Temperature control is typically passive due to the low cutting speeds which promote near steady-state thermal cutting conditions. Applications in which these systems are being employed include 2.5D profiled signage, architectural products and mouldings, surfboard core manufacturing and packaging. Several prominent manufacturers of these flexible automated foam cutting systems include 'Croma' of France (17), 'FoamLinx' of the USA (18) and 'Megaplot' of Poland (19). Figure 2.3-5 below shows a collection of equipment from the aforementioned manufacturers.

Croma, "http://www.foamcutter.com."

FoamLinx, "http://www.foamlinx.com."

Megaplot, "http://www.foamcutter.pl."

Figure 2.3-5 - Conventional taut hot-wire sculpting devices

2.3.5 Rapid Prototyping with Sloping Surfaces (Trusurf) (20, 21)

The Trusurf system was developed by R.L. Hope et al of the University of Queensland, Brisbane, Australia. R.L.

The Trusurf system utilises the layered object manufacturing (LOM) methodology, which is common to many conventional RP processes. The system was developed primarily to produce large (> 1 m^3) free-form models out of polystyrene. It uses a high-pressure, 5–axis water-jet cutter to cut the model's cross-sections from thick layers of polystyrene (10, 20 and 30 mm stock sizes). The 5–axis cutter cuts the cross-sections with sloping edges (as opposed to square cut) to eliminate the stepped surface finish common to many LOM systems. Once the thick cross-sections have been cut, they are assembled and bonded by hand to produce the finished model. The innovative advantage of the Trusurf system lies in the fact that it can produce large, relatively accurate models due to using thick sloping layers.

The creators of Trusurf decided to use direct CAD model slicing as opposed to the slicing of the intermediate tessellated .STL file. They use IGES (**I**nitial **G**raphics **E**xchange **S**pecification) CAD files, which represent the model's surfaces as B-spline surfaces, which are exact, unlike the tessellated approximated surfaces of .STL models.

The surface of a CAD model in the IGES format can be described sufficiently in terms of the B-spline surfaces, which comprise it. A B-spline surface is defined by the following equation:

Equation 1 - B-spline surface definition

$$P(s,t)=\frac{\sum_{i=1}^{n+1}\sum_{j=1}^{m+1}W_{ij}.P_{ij}.b_{ik}(s).b_{jl}(t)}{\sum_{i=1}^{n+1}\sum_{j=1}^{m+1}W_{ij}.b_{ik}(s).b_{jl}(t)}$$

W_{ij} are weightings, P_{ij} are 3D net points, which define the bounding polygon of the surface, b_{ik} and b_{jl} are basis functions of order *k* and *l*. If the weightings, net points and basis functions are known for a particular surface, the parameters *s* and *t* define a point on that surface exactly. All of the aforementioned information is contained within an IGES file. It should be noted that the parameters *s* and *t* vary from zero to one.

Tool paths are generated as follows:

1. The user orientates the CAD model so that the desired slicing planes are normal to the z-axis (layer stacking direction).
2. The Trusurf software traces cross-sections by keeping the z altitude constant. The start point of the cross-section loop is found by setting the parameter s = 0. The value of t is then iteratively solved for which satisfies the current z altitude. Because s and t exactly define a point on the surface, the x, y and z coordinates for the point are known and can be stored.
3. s is then increased by 1/(# points used around the cross-section) and t is again iteratively solved for hence locating the second x, y and z coordinate. The cut quality can be improved by increasing the number of points used, since the water-jet cutter moves linearly from point to point.
4. Once the contour has been traced and the x y and z points defining the cutting path have been stored, the cutter direction, angle and rotation is determined. This is achieved by computing the cross product of the surface normal and surface tangent vector at each point. Steps 2 – 4 are repeated for each layer.

Because the cutter only produces a linear approximation of the surface, there is an associated error. This error is minimised by altering the layer thickness. The thickest layer (30 mm) can be used when the error is negligible but the thinnest layer (10 mm) must be used when the error is the greatest.

The work documented by Hope. R.L et al concluded that the next step forward would be to create a system, which utilises a controllable curved cutter capable of cutting the cross-sections with curved edges instead of linearly sloped edges. This would produce models with superior shape accuracy.

One major model they produced was of a life size dolphin.

Advantages

- Fast build times using thick layers
- Uses stock layer thicknesses of 10, 20 and 30 mm
- Sloping edges of contours improves shape accuracy for large models
- 5–axis water cutter is fast and easy to control
- Capable of building large models

Disadvantages

- Low accuracy for small models due to linear approximation on edge slopes
- Labour intensive assembly required
- Process is limited to plastic foams

2.3.6 Free-form Thick Layer Object Manufacturing Technology For Large-sized Physical Models (22)

This paper was submitted by the Faculty of Design, Engineering and Production at Delft University of Technology in the Netherlands. It outlines a proposed system, which is similar to the Trusurf system in the fact that it aims to use thick layers of stock thickness polystyrene for the build material. It also plans to use thinner layers where the surface curvature is greatest and thicker layers where the surface curvature in minimal. The cutting of the cross-sections is different however, and is to be performed using a customised, flexible, shape-controlled, electrically heated cutting tool. It is envisioned that the cross-sections once cut, will be assembled and bonded by hand to produce the finished model.

A major innovation of the proposed system lies in the cutting tool. The proposed tool consists of a flexible metallic blade of fixed length, which is clamped at each end by supports. Stepper motors are used to rotate the supports by set amounts which induces the blade to take up various shapes. The shape that the blade takes is related to the minimum strain energy within the blade, which can be accurately calculated and predicted. The proposed cutting tool and a map of the achievable blade shapes is shown below in figure 2.3-6.

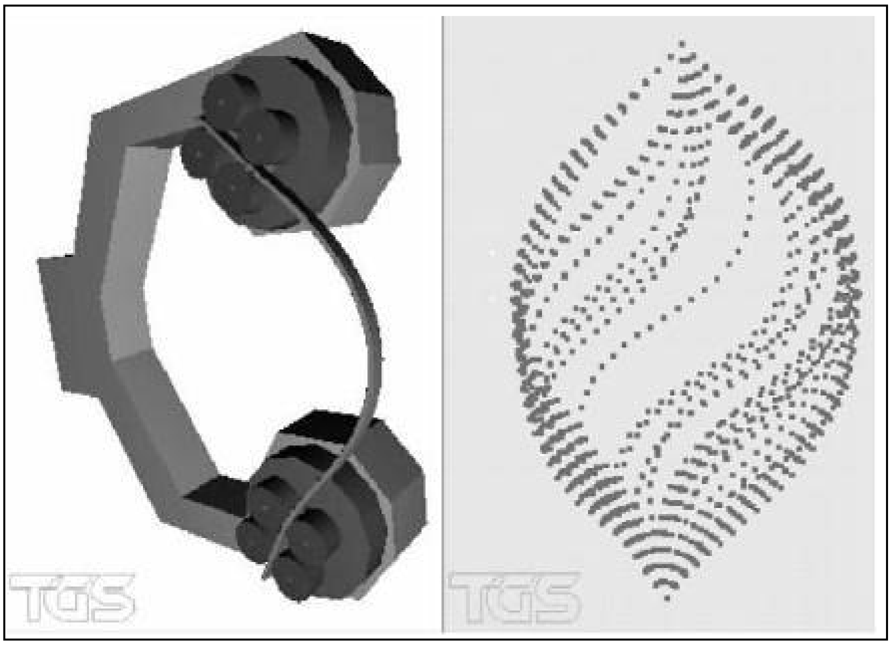


Figure 2.3-6 - The proposed cutting tool and map of achievable blade shapes

The cutting paths are generated as follows:

1. The CAD model is oriented so that the desired slicing planes are normal to the z-axis (stacking direction).
2. A slicing algorithm slices the model into maximum thickness layers (maximum thickness depends on the stock sizes available).
3. Software traces around the perimeter of each cross-section and seeks to match the edge contour with a possible blade shape. The blade shapes are stored in a library and are indexed to the blade-end-support rotations. The number of points around the contour to perform the matching procedure which is set by the user. Obviously, the more points chosen, the more accurate the profile will be, since the cutter moves linearly between points. All match attempts are initially made

with the mid point of the blade coincident with the bottom plane of the slice. If a match cannot be made, two subsequent actions are taken. The first is to search other regions on the blade for a match. If this does not yield a match, the thickness of the layer is reduced and the process is repeated until a match is found. It is theoretically possible to obtain accurate matches in this manner.

4. The complete tracing of a contour results in a set of machine controls in terms of blade support rotations, layer thicknesses and x y and z coordinates for each point around the layer. The thickness for the layer is set as the minimum layer thickness required as obtained from step three. Once all of the layers have been processed, the cutting can begin.

It is proposed that the CAD model to be sliced will be sent to the slicing software using the STEP (**St**andard for the **E**xchange of **P**roduct model data) transfer format, combined with the geometric representation of NURBS (**N**on-rational **U**niform **B**-**S**pline) which can exactly represent surfaces in terms of simple parameters.

The authors identified the complex problem of hot-tool plastic foam cutting. In particular, they mentioned the problems faced with controlling power input to the tool to maintain optimum cutting conditions in terms of cutting forces and surface finish. It appears however, that the authors have not carried out extensive research into hot-tool plastic foam cutting mechanics.

Advantages

- Accurate surfaces possible
- Capable of building large models
- Using LOM eliminates a lot of complexity in generating tool paths
- A blade (as opposed to a wire) generates a lower cutting force and results in a better surface finish

Disadvantages

- Complex edge contour matching algorithm which is computationally demanding
- The rapidity of blade shape change required, may not be achievable due to the fact that the blade movement normal to the direction of travel will be retarded by the foam
- Blade distortion is possible with higher cutting forces
- Labour intensive assembly required
- Internal holes and hollows are not possible

2.3.7 ModelAngelo (23)

This paper was submitted by the Department of Mechanical Engineering at the American University of Beirut in Lebanon. It outlines a unique subtractive foam sculpting system called "ModelAngelo", which was designed and prototyped. The system operates in a similar fashion to a conventional metal lathe. However, the rotational axis (α), about which the stock rotates, is fully controllable and can be stopped, started, and rotated incrementally at programmed speeds. The cutting tool is attached to an assembly, which provides it with 3-DoF. A schematic of the complete system is shown in figure 2.3-7.

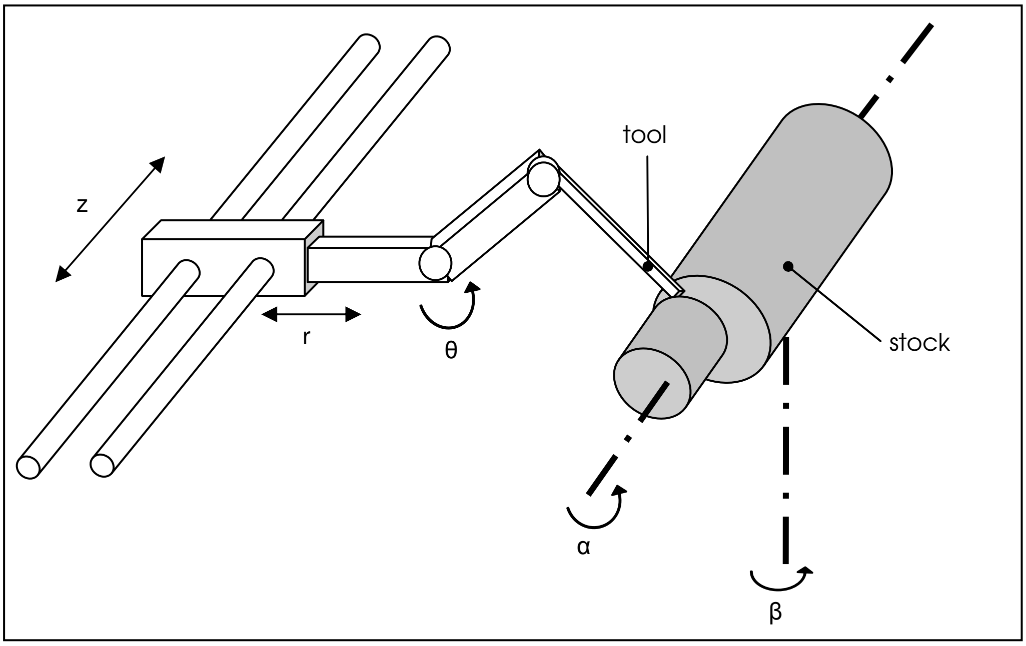


Figure 2.3-7 -Schematic of the ModelAngelo Apparatus

As can be seen from figure 2.3-7, the system uses a combination of rotational and linear axes to effect the sculpting of objects. The carriage, which supports the tool and linkages, can travel along the 'z' axis, which allows tool access to the entire length of the model. The tool is controlled by two linkages. The linkage connected to the carriage can move in and out linearly along the 'r' axis. The next linkage can rotate about the 'θ' axis. This linkage has a belt, which is connected to the 'θ' axis driver and at the other end to the pivot where the tool is attached. This results in the tool being oriented through the objects centreline at all times, regardless of the rotation of the linkage about the 'θ' axis. The 'β' axis is used to turn the object through 90º. The tool can be passed over the object in two orientations to smooth out the cusp from the cutting in the first orientation.

The tool consists of two short Nichrome wires, which are electrically heated above the melting point of the plastic foam used. The bottom wire cuts the foam away while the top wire efficiently removes the swarf by curling it away from the object. The cutting tool is schematically illustrated in figure 2.3-8.

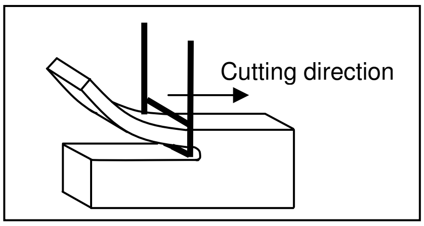


Figure 2.3-8 - ModelAngelo cutting tool

The system works by removing material from the stock, layer by layer similar to conventional metal turning. The main difference is the fact that the tool can be controlled in conjunction with the rotational axis to produce asymmetric models.

The software to drive the system was custom-written and runs as a Visual Basic Application (VBA) module within AutoCAD. The steps to generate tool paths and to sculpt an object are as follows:

1. The model is aligned with it longest dimension parallel to the 'z' axis.
2. The software slices the AutoCAD model into thin slices. Radial lines separated by 1.8º (α-axis stepper motor resolution) are transposed onto the slices. These radial lines originate from the centreline of a cylinder, which would fully enclose the object.
3. The cross-sections are traced using a mathematical algorithm programmed in the VBA module. This works by finding the intersection of the radial lines with the cross-section's perimeter. The intersection points for each slice are stored as a vector containing an 'r' value and an 'α' value. These are later used to generate the control commands for the other axes.
4. The object is then discretized into a series of cylinders, which are concentric with a cylinder, which would just enclose the entire model. These cylinders are used as cutting layers for the sculpting process.
5. The sculpting begins by the tool cutting around the first cross-section, but only to a depth of the first cylinder that intersects with the cross-sections. The cutter traverses along the z-axis and traces out each cross-section but only to the depth of the first cylinder. The procedure is repeated again with cuts made to the depth of the second cylinder. Cuts are made until there are no more layers to remove.

The ModelAngelo system also controls the temperature to ensure a good quality cut. The authors derived an equation for their cutting tool in which the wire current (temperature) is a function of the tool velocity. Since the velocity is a process variable, the current required to maintain a good surface finish can be calculated based on the current tool velocity and hence controlled.

The authors envision that the technology could be used for art sculpting, prototypes for fit and form evaluation, and casting processes for biomedical and engineering applications.

Advantages

- Simple system mechanisms
- Cost effective
- Good swarf removal
- Effective wire temperature control

Disadvantages

- Slow and complicated tool path creation
- Slow layer by layer material removal process
- Sub-standard surface finish
- Limited object complexity achievable

Several finished products sculpted by ModelAngelo are shown in figure 2.3-9.

Figure 2.3-9 - Polystyrene parts sculpted by ModelAngelo

2.3.8 Investigation into Development of Progressive-type Variable lamination Manufacturing Using Expandable Polystyrene Foam and its Apparatus (24)

This paper was submitted by the Department of Mechanical Engineering at the Korean Advanced Institute of Science and Technology in Taejon, Korea. It outlines a prototype system, which uses a hot wire to cut out 'thick' EPS cross-sections, which are consequently bonded together to form the finished object. The hotwire cutter does not cut the sections with vertical edges but rather cuts sloping edges in an attempt to increase the model accuracy and improve surface finish.

The authors of the paper believe conventional RP technologies (such as those outlined in section 2.2) have the following key disadvantages: Low build speeds, stair-stepped surface finishes, time consuming post-processing requirements, high installation costs and high maintenance costs. They believe their developing technology targets all of these disadvantages. The process consists of the following three main steps:

1. *Material feeding and storing:* The material chosen for the process is 2 mm thick EPS which is stored in a large role. The role is fed into the cutting area via several sets of rollers. One of the rollers in the main roller set is heated. This acts to relieve the compressive stress, which is generated on one side of the foam as a result of being stored in a tight roll. The next set of rollers acts to both apply the bonding agent to the underside of the layer and to control the thickness of the layer by exerting pressure. Controlled suction part holders then hold the dimensionally accurate stock layer in place from above.

2. *Shape generation:* The next step involves cutting out the required shapes. Unlike the proposed system of Broek et al (22), the process is capable of generating objects with internal holes and hollows. This is achieved by creating layers, which consist of more than one piece. Figure 2.3-10 illustrates this concept.

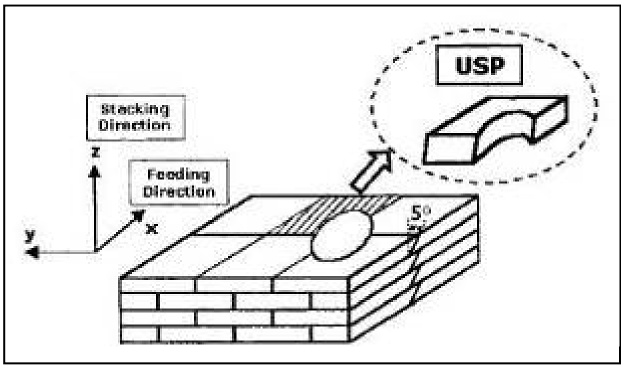


Figure 2.3-10 - Mulit-piece layer concept

As can be seen from the figure, the layers consist of several individual pieces, which are assembled together like a jigsaw. The joining edges in the feeding direction are cut with opposite 5º angles and are staggered like brickwork in the transverse direction to improve the strength of the finished object. The pieces are cut using a 4-axis hotwire cutter as shown in figure 2.3-11.

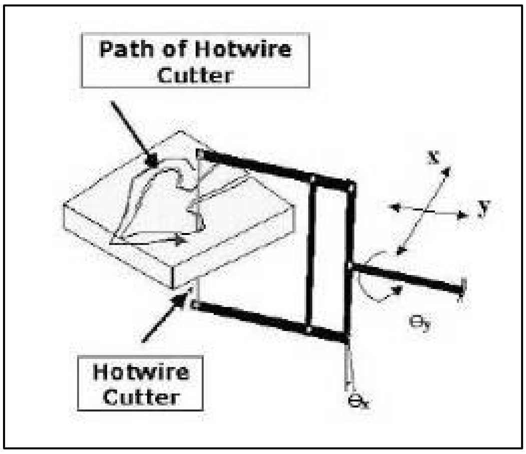


Figure 2.3-11 - Cutting tool and axis orientations

The shaping information which drives the cutter for each piece, consists of point data (x and y coordinates) of the contour, slopes in the surface (two angular coordinates) of each point and hotwire temperature and feed-rates. The generation of the cutting data is achieved as follows:

a. The CAD model is exported in the typical .STL format.

b. Custom designed software slices the CAD model up into a collection of 2 mm thick slices.

c. Each layer is cut again at the mid-plane in order to determine approximate surface slopes around the layer.

d. The facets generated by the .STL format are used to generate the cutting tool orientation by computing the cross-product of their normal vector and unit vector of the cutting direction. In this manner a first order approximation of the local surface slope is generated.

e. The slices are cut into individual pieces.

f. The data obtained from the above steps is combined to generate the cutting tool path.

3. *Stacking and bonding:* Once the individual pieces have been cut out, they are stacked on a controllable x-y table. Once a layer has been assembled the table is moved below a pressing mechanism which is used to press the bonded layers in order to enhance the bonded strength of the finished model.

The un-cut material is then cut off and removed by gravity and the steps are repeated until the object is fully built.

The authors conducted a comparison between their system and several conventional RP systems, including, LOM and FDM. The particular attributes of the processes, which were compared, were; set-up time, build time, post-processing time, and dimensional accuracy. The results showed that the process required approximately $1/10^{th}$ the set-up time of LOM and FDM, build time was reduced six fold compared to LOM and 38 fold compared to FDM. With respect to dimensional accuracy, the process was equally accurate when compared to LOM and more accurate than FDM in all the measured dimensions. It must be noted that this comparison was based on all processes building the same model.

Figure 2.3-12 shows several parts which were produced by this process.

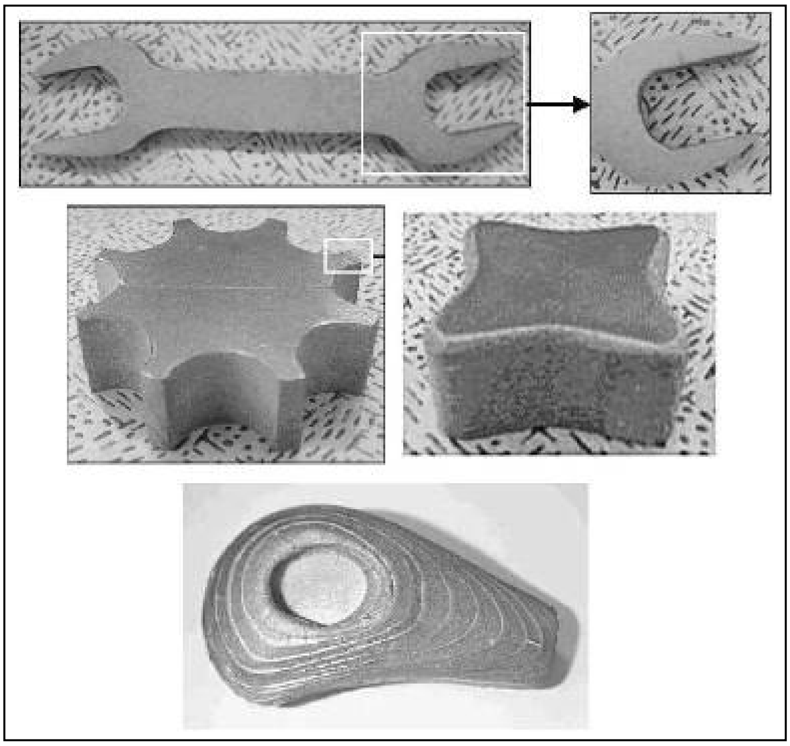


Figure 2.3-12 - Various object produced by the method

Advantages

- Fast and accurate
- Good surface definition possible using first order approximation of edge contour and 2 mm thick layers
- Highly automated process including stacking and bonding
- No post-processing required

Disadvantages

- Complex system
- Process is limited to plastic foams
- Produced parts have limited uses due to material properties of EPS

2.3.9 Literature and Technology Review Summary

The above literature and technology review covered several systems, which are all similar to the proposed system in at least one of the following four ways:

- Uses an articulated robot for material removal
- Uses extruded or expanded polystyrene for object material
- Uses an electrically heated tool (e.g. hotwire cutter)
- Process is partially or fully automated from CAD model through to finished object

Three of the cases reviewed, used the conventional RP layer-by-layer methodology to accomplish the building of physical models. The exceptions were J Zhu et al with their 8-axis robot based rough cutting system, the Programming Plus, Delcam and Kuka collaboration, J. S. M. Vergeest et al with their 7-DoF robotic machining process and R. F. Hamade et al with Modelangelo.

The techniques employed to generate tool paths for material removal were broad, varied, and were generally developed from scratch, specifically for the particular process. The exception was the Programming Plus, Delcam and Kuka collaboration, which used Delcams' existing CAM package, PowerMill, as their basis.

The majority of the processes aimed to use the models produced for the purposes of lost foam casting, visual concept verification, physical end use models and in some cases, fit and form analysis. The processes that use EPS as the object material are especially suited to producing models for the lost foam casting process.

All the literature agreed on the fact that surface finish and dimensional accuracy were paramount to a successful system. Two main approaches were taken to achieve these two desirable attributes:

- The first approach was based on the notion that "many small steps" would achieve a good surface finish and dimensional accuracy. The many small steps initiative was applied to both layer-by-layer type processes and purely subtractive processes. In the former, the initiative was applied to the thickness of the layers used (i.e. lots of thin layers results in an object with good surface finish and dimensional accuracy). In the latter, the initiative was applied to tool path density (i.e. if the tool path density is great enough, the cusp produced by adjacent paths is eliminated, hence resulting in good surface finish and dimensional accuracy).
- The second approach was only applied to the layer-by-layer type processes and involved creating thicker layers with ruled or contoured edges. This effectively improved the surface finish and dimensional accuracy of the model without having to increase the number of layers used. This approach proved to be computationally more demanding than the first approach in terms of generating tool paths and machine control data, but could produce models quicker and with comparable surface finish and dimensional accuracy.

Several ideas, which were gleaned from the review, could prove useful if applied to the proposed system in this thesis. These included:

- The use of a turn table or multiple axis table as used by J. S. M. Vergeest et al and J, Zhu et al. In both cases, the use of such work piece supporting tables allowed far greater reach-ability by the articulated robots being used, which resulted in the ability to sculpt more complex geometry from a single blank.

- The innovative swarf curling/removal technique employed by R. F. Hamade et al with Modelangelo. Swarf removal of foam plastics is an important aspect, since the likelihood of the swarf re-bonding to the parent material following a cut is fairly high.
- The variable shape tool concept proposed by J. J. Broek et al. This innovation has the potential to produce an exceptionally flexible sculpting system. For example, the same blade that performs large rough cuts could be quickly modified to perform finish cuts and intricate surface detail.
- The majority of the systems utilised some form of interference/collision detection analysis through a simulation process. This is extremely important, especially when a complex system consisting of many axes is employed.
- Many of the systems exhibited a high level of automation. In particular the automatic generation of tool paths directly from the CAD model was common among the systems. The automation of data creation (tool paths, control programs etc.) is very important if the fast, reliable and automated production of sculpted objects is to be realised.

3 EXPERIMENTAL WORK

3.1 Introduction

The experimental work presented in this thesis forms the backbone of the whole project. The work was split into two main sections, namely, 'Preliminary 3D Sculpting' and 'Advanced 3D Sculpting'. The former aimed at proving the concept of 3D robotically effected sculpting of foam plastics. This experimental work was essentially evolutionary in nature, in that the direction was guided by the results as they were obtained. The work consisted of both developing the procedure to sculpt objects from a CAD model input and carrying out said procedure. The effects of varying test parameters such as tool shape, size, path spacing, feed rate and tool temperature on the surface finish were also investigated.

The latter aimed at automating and integrating the various components of the system. The main focus of which was on the automation of the tool path generation and optimisation step. This experimental work consisted of developing the procedure for the semi-automated and integrated system as well as testing the developed procedure. The Advanced 3D Sculpting work went another step further by investigating a practical application for the plastic foam cutting system, namely, the sculpting of a patient customised medical radiation therapy head and neck support.

The ensuing section describes the generic experimental setup in detail.

3.2 Generic Experimental Setup

The experimental setup was essentially the same for all tests undertaken. The only difference was the shape of the cutting blade used and the spatial location of the mounted blank. The setup comprised a 6–axis articulated robot (with control system), electrically heated cutting tool held in a pneumatic gripper, foam blank, blank mounting fixture and supporting table. Figure 3.2-1 below shows the generic experimental setup. The various components in the experimental setup will be described and explained in the subsequent sections.

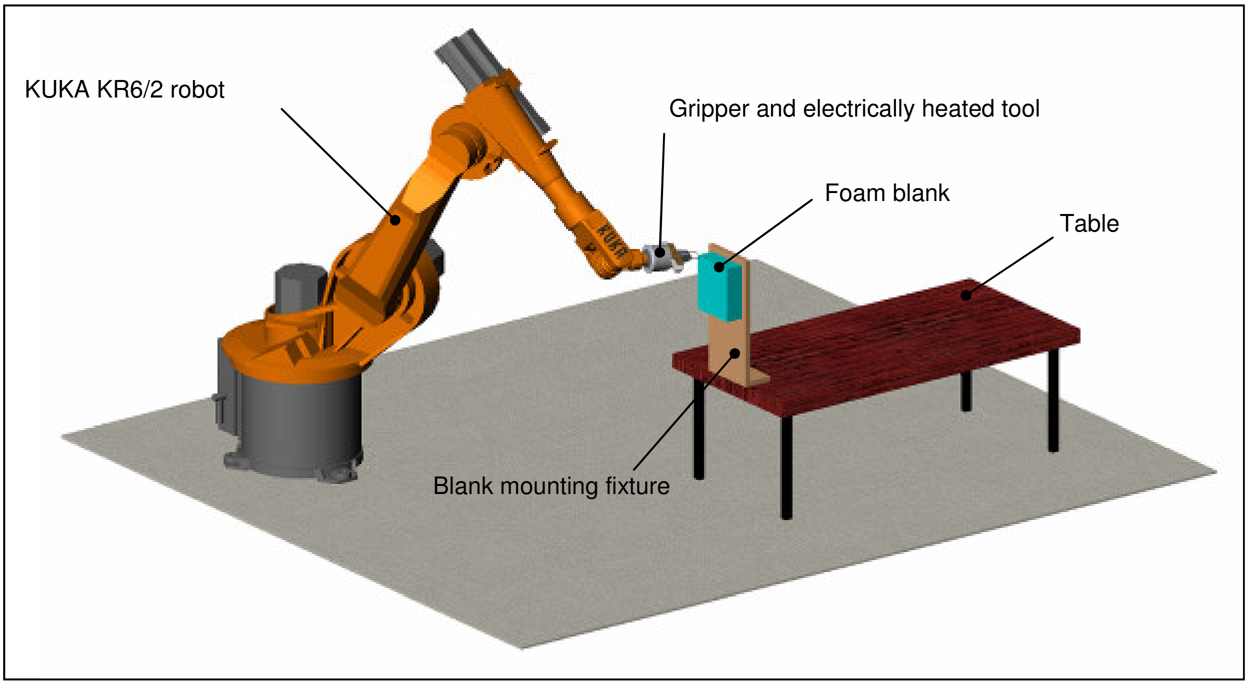


Figure 3.2-1 - Generic experimental setup

Figure 3.2.-2 below shows a close-up view of the gripper and electrically heated tool used in the trials.

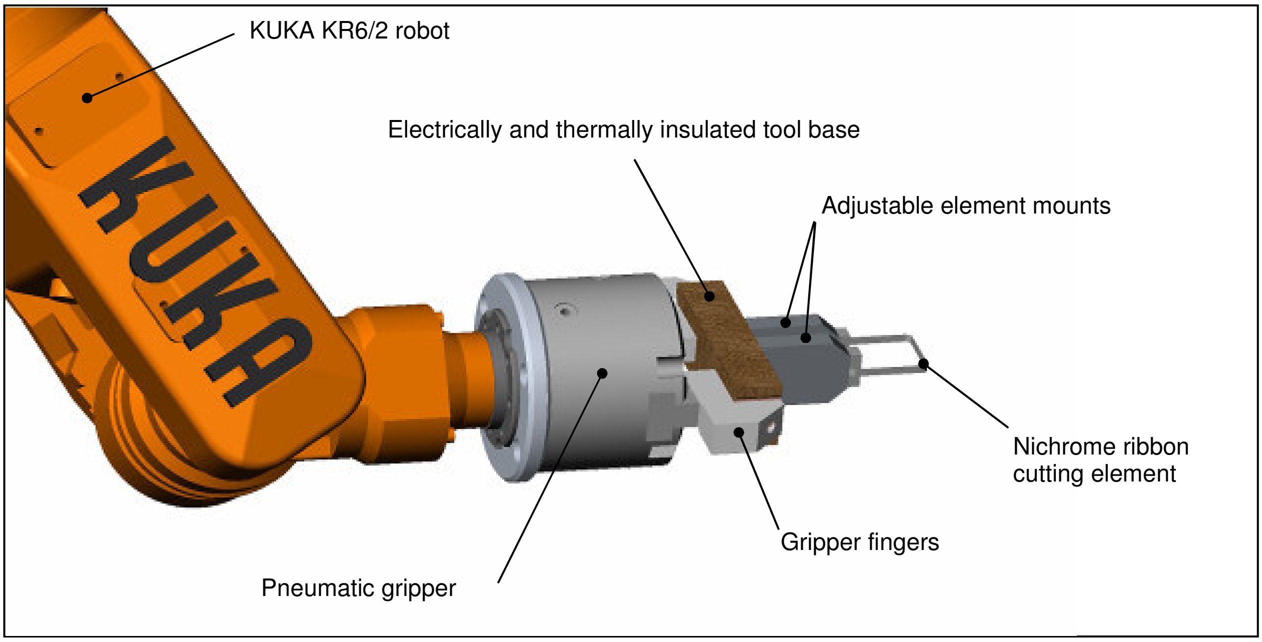


Figure 3.2-2 - Close-up of gripper and electrically heated tool

3.2.1 Robot and Control System

The robot used was a German designed and manufactured 6–axis KUKA KR6/2 articulated robot which was supplied by Scott Automation along with a KUKA KR C2 controller. Figure 3.2-3 below shows the dimensions and working envelope of the KUKA KR6/2 robot.

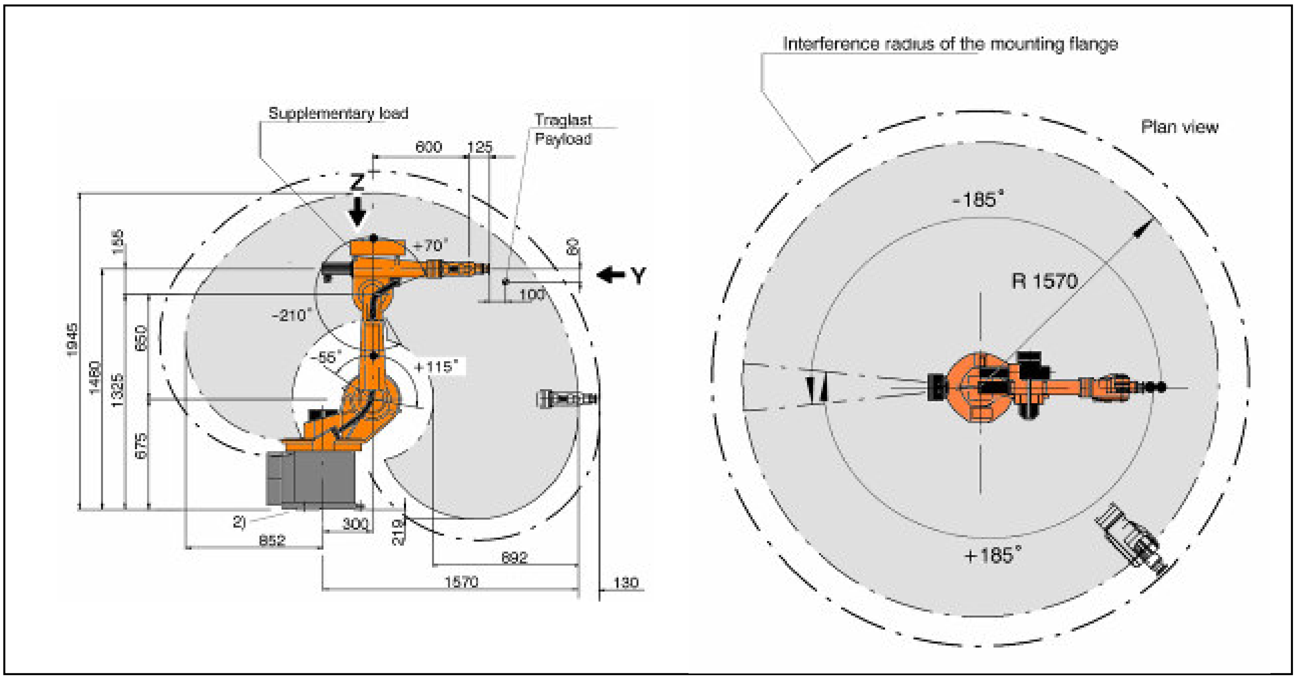


Figure 3.2-3 - KUKA KR6/2 articulated robot (Obtained from KUKA datasheet)

The working envelope is a reasonably large 'fist' shaped envelope. The KUKA KR6/2 can handle a maximum 6 Kg payload, can move at velocities of up to 2 ms^{-1} and has a repeatability of 0.1 mm (accuracy). The robot is entirely electrically powered and operates on 3 – phase 500V, 50 Hz power. Table 3.2-1 provides the robot's key specifications.

Table 3.2-1 - KUKA KR6/2 specifications

Payload	6 Kg
Repeatability	± 0.1 mm
Maximum reach	1945 mm
Axis data	**Range/speed**
Axis 1	±185º / 152º/s
Axis 2	+115º -55º / 152º/s
Axis 3	+70 º -210º / 152º/s
Axis 4	± 350º / 250º/s
Axis 5	± 130º / 357º/s
Axis 6	± 350º / 660º/s

The robot has six controllable DoF; three positional degrees (X, Y and Z) and three rotational degrees (A, B and C). The rotational DoF are simply rotations about each of the three positional axes. 'A' is the rotation about 'Z', 'B' is the rotation about 'Y' and 'C' is the rotation about 'X'. The order that the rotational DoF are listed is important. The KUKA control system follows the order: Z – Y – X, i.e. rotation about the Z–axis first followed by rotation about the transformed Y-axis and finally rotation about the transformed X-axis. Figure 3.2-4 below explains the concept.

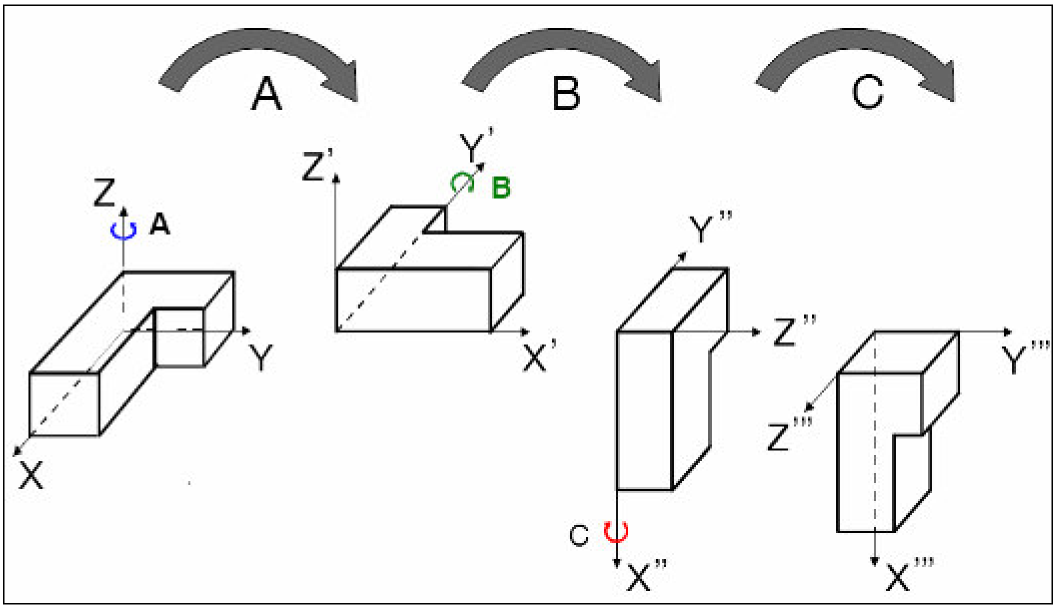


Figure 3.2-4 - Rotation order for rotational degrees of freedom (Obtained from KUKA manual)

All movements which the robot performs are with respect to a coordinate system. There are four coordinate systems which are used by the robot, namely, 'World', 'Robot', 'Base' and 'Tool' coordinate systems. The World coordinate system is set at an arbitrary point and cannot be moved. It represents the reference system for both the robot system and the peripheral equipment of the cell. The Robot coordinate system has its origin in the base of the robot and serves as the reference coordinate system for the mechanical construction of the robot. The Base coordinate system is programmable and is used as the reference system to define the position of a work piece. All programmed motion commands are relative to this coordinate system. The tool coordinate system is programmable and is used to define the location and orientation of the tool with respect to the tool mounting flange. Typically the Z axis of the tool coordinate system points out of the tool mounting flange. Figure 3.2-5 illustrates the aforementioned coordinate systems.

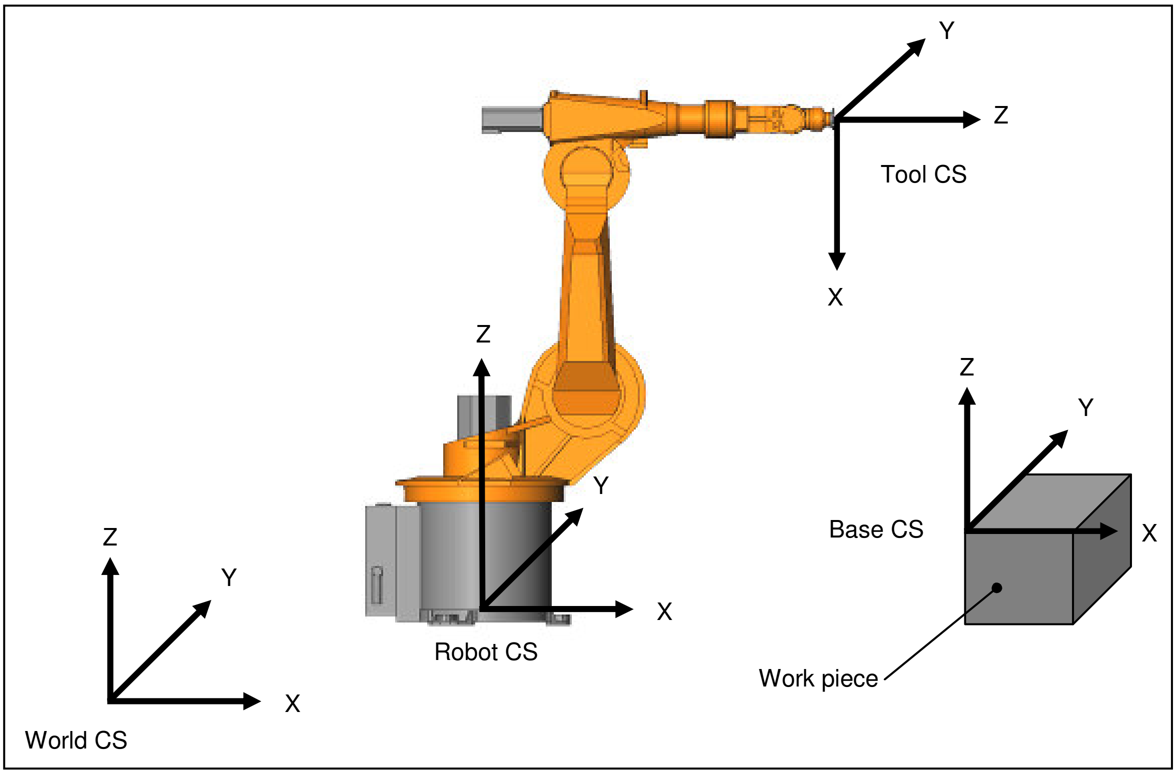


Figure 3.2-5 - Robot coordinate systems

The robot controller accepts three simple motion commands, namely, point-to-point (PTP), linear interpolation (LIN) and circular interpolation (CIRC). Using PTP commands is the quickest way to move the robot from one position to another. The PTP command can be used with either axis specific coordinates or Cartesian coordinates. An example of an axis specific PTP command is shown below:

PTP {A1 90, A2 45, A6 -125}

This PTP command simply moves axis A1 90º, A2 45º and axis A6 -125º. PTP motion is completely synchronous meaning that all the axis movements will stop and start at the same time; hence the axis which needs the longest time to get to the programmed position governs the overall movement time. Often it is easier for the user to think in terms of Cartesian coordinates when programming movements. An example of a Cartesian coordinate specific PTP command is shown below:

PTP {POS: X 1200, Y 0, Z 395, A 24, B 69, C -100}

This command simply moves the tool centre point (TCP) to the position {1200, 0, 395}, and orientates it in line with the set of angles {24º, 69º, -100º}. By default the TCP is set as the centre of the mounting flange on the end of the sixth axis. The TCP can be changed to accommodate any tool by programming the location and orientation of the tool coordinate system previously described.

The controller handles a LIN motion command by calculating a straight line from the current position (the last programmed point) to the position specified in the motion command. Cartesian coordinates are used to specify the motion. An example is shown below:

LIN {X 250, Y 500, Z 323, A 43, B 90, C 25}

LIN {X 260, Y 520, Z 345, A 60, B 95, C 35}

If the robot was already at the first point, it would calculate a straight line to get to the next programmed point. Unlike PTP motions, LIN and CIRC motions can be controlled in terms of velocity and acceleration. The programmed velocities and accelerations are with respect to the TCP. LIN commands can easily be used to define a 3D path in space. For example, if an irregular curve needs to be followed, it can be programmed by discretizing the curve into a collection of small straight lines which can be followed easily via the LIN motion command. Greater path accuracy can be achieved by increasing the number of straight line segments which make up the path. The CIRC command is a simple command which allows the TCP to follow a defined curve of fixed radius. To programme a CIRC command the user need only specify the end point of the curve and an auxiliary point somewhere on the curve between the start point and end point. The start of the curve is taken as the current position of the robot. An example of a CIRC command is shown below.

CIRC {X 925, Y -238, Z 718} {X 867, Y -192, Z 718}

The first bracketed set of coordinates defines the auxiliary point while the last set defines the end point. Orientations A, B and C can also be used to specify the end point orientation.

3.2.2 Tool, Gripper and Power Supply

The cutting tool consists of a plastic electrically and thermally insulated base which carries the electrical contacts and supports the element mounting blocks. The electrical contacts are brass and are connected to the power leads shown in figure 3.2-6. The element mounting blocks are aluminium and can be moved closer together or further apart depending on the size of the cutting element to be used. The cutting element (blade) is made from 3 x 0.4 mm Nichrome ribbon capable of being heated to 1000ºC. The cutting element is clamped down with two brass connections attached to the ends of the power leads. Thin mica strips are sandwiched between the ends of the cutting element and the mounting blocks to minimise heat loss into them. Various element profiles were used throughout the trials (all elements were made from the stock size of 3 x 0.4 mm Nichrome ribbon). Figure 3.2-6 below shows the abovementioned tool.

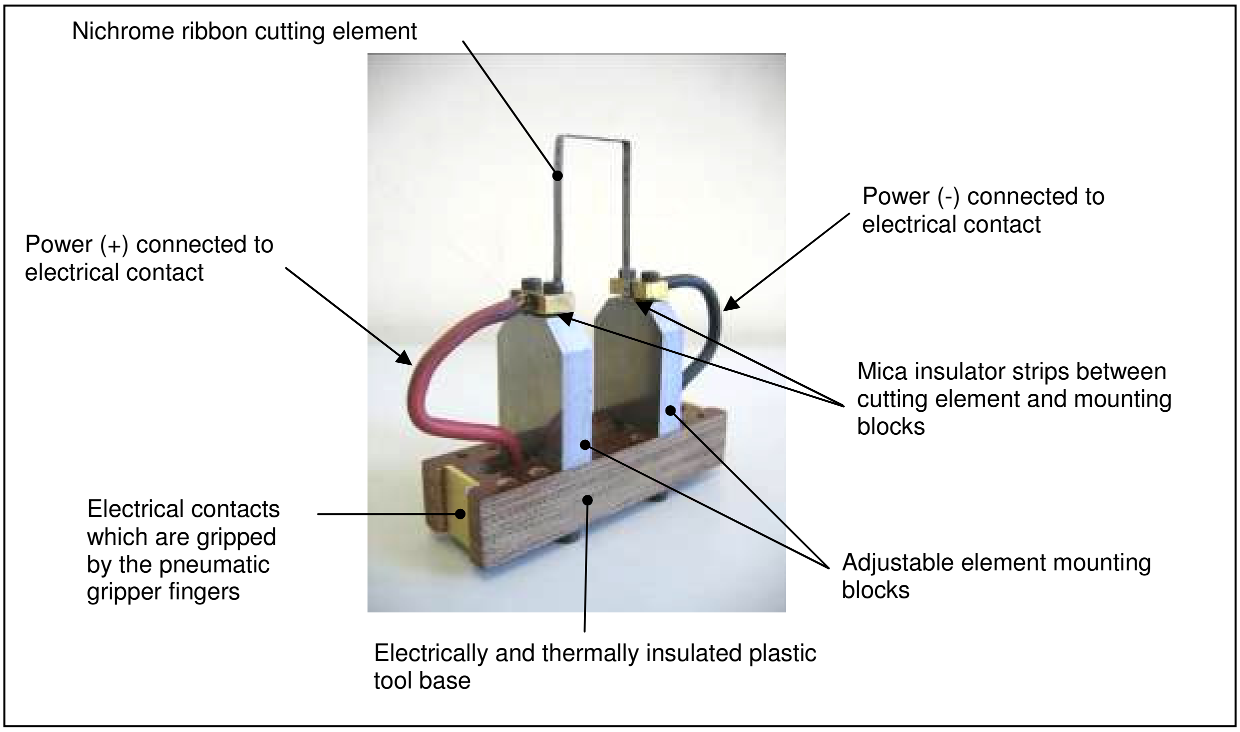


Figure 3.2-6 - Sculpting tool

A pneumatic gripper (model #MHS2-63D, supplied by SMC Pneumatics) was attached to the mounting flange of the robot. Specially designed gripping fingers which incorporate electrical connections grip the sculpting tool and provide power to the cutting element.

The Nichrome ribbon was electrically heated by way of a custom built DC power supply with a maximum current output of 40 amps at 6 volts. For the majority of the testing, the current was controlled via a simple manually adjusted rotary switch.

3.2.3 Modelling Media

Two types of foam were used for the sculpting media, namely, EPS and XPS. EPS is a rigid, closed cell, thermoplastic foam material which is manufactured by heating styrene pellets with steam so they expand within a mold to form a block of low density foam. EPS is a low cost material and is consequently used for many applications, including, packaging of electronic goods, flotation devices, film props, building insulation, signage, architectural features and acoustics. EPS usually comes with a white appearance but can be coloured with dyes.

XPS has the same chemical composition as EPS but differs mechanically due to the manufacturing operation by which it is formed. XPS is manufactured by extruding molten polystyrene (originally in resin granule form) mixed with a blowing agent through a die in a continuous process under carefully controlled temperature and pressure conditions. The resultant product is denser (smaller air pockets) and more homogeneous than EPS. XPS is not as cost effective as EPS but is still considered low cost. Applications for XPS are similar to those of EPS, however, XPS is more extensively used as building insulation and is commonly known as 'Styrofoam'. XPS is generally cut using heated tools to obtain the desired artefact while EPS is often molded in a net shape process which requires no subsequent cutting.

EPS and XPS were chosen because they are light, relatively strong, low cost and of most importance, can be cut easily with electrically heated tools. Table 3.2-2 below provides the key specifications of the two products used.

Table 3.2-2- Sculpting media specifications

Attribute	EPS (byBondor)	XPS (by DOW)
Structure	Amorphous, closed-cell foam	Closed cell
Density	20 kg/m^3	30 kg/m^3
Melting point	100 ºC	100 ºC
Unstable against	Esters, Ketones, Ether, petrol, aromatic hydrocarbons, chlorinated hydrocarbons	Esters, Ketones, Ether, petrol, aromatic hydrocarbons, chlorinated hydrocarbons
Resistant against	Acids, bases, methyl alcohol, ethanol, propane, silicone oils	Acids, bases, methyl alcohol, ethanol, propane, silicone oils
Compressive strength	50 KPa	210 KPa
Thermal conductivity	0.038 W/mK	0.027 W/mK

3.3 Safety Precautions

The KUKA KR6/2 industrial robot is capable of moving at speeds of up to 2 ms^{-1} and can accelerate extremely quickly which presented a serious safety issue considering the small size of the robot's working envelope. The cutting of polystyrene by means of vaporisation and melting posed another health and safety issue. The safety measures put in place to ensure no personal injury or damage to equipment by the robot or cutting of polystyrene included:

- The robot's working envelope was clearly marked with 'danger' tape on the floor. In addition several photoelectric sensors wired to the emergency stop circuit of the robot's control PC were used as 'light barriers'. The robot was shutdown immediately when someone crossed the light barrier. The barriers needed to be reset to resume operation once they had been triggered.
- All new control programs created were run at a reduced velocity and were run in the 'Test 2' control state. The 'Test 2' control state requires the user to engage a paddle like switch with their fingers while they hold their thumb on a button to execute the program. The robot stops instantly if the paddle like switch is released or the pressure on the execution button is relieved. In addition, the robot is also stopped if the paddle like switch is depressed with excessive force (this is designed to accommodate panic responses by the user).
- Three emergency stop buttons within easy reach around the room were wired to the emergency stop circuit of the robot's control PC. If the buttons were pressed, the system would need to be rebooted in order to reset them.
- A large extractor fan with adequate ducting to the outside was used to remove fumes and smoke during cutting.
- A fire extinguisher was on hand to extinguish any possible fire caused by the cutting of the polystyrene.

3.4 Preliminary 3D Sculpting

3.4.1 Objectives

The main objective was to prove the concept of 3D sculpting using the aforementioned experimental setup. Prior to the preliminary 3D sculpting no such activity had been undertaken. Previous undertaken work (25, 26) which is outside the scope of this thesis, involved the cutting of EPS and XPS with a pneumatically tensioned taut hot wire.

In addition to proving the concept, it was intended that the testing would provide an insight into the unexplored area of cutting plastic foam with an electrically heated loop of Nichrome ribbon as opposed to a conventional taut hotwire. The tests were subsequently exploratory and evolutionary in nature. Qualitative observations of the cut surfaces were used to change the testing conditions from test to test in order to explore the effects and discover the parameters which produced accurate and smooth sculpted surfaces. The objectives can be summarised as below:

- Prove the concept of 3D robotically effected sculpting of foam plastics with an electrically heated tool, comprising a loop of Nichrome ribbon and using a CAD model as the primary input to the process.
- Investigate via exploratory and evolutionary testing, the parameters that produce accurate and smooth sculpted surfaces.
- Record the test parameters along with qualitative observations.

3.4.2 Procedure

The design and development of the following procedure comprises a significant section of the authors work. The procedure outlines the steps taken to sculpt freeform surfaces using a CAD model of the object as the primary input to the process. The procedure was developed with the primary focus of proving the concept in mind. Subsequently the developed procedure only utilized resources available at the time and was not focused on efficiency or ease of use. The experimental procedure comprises the following four steps:

1. Generation of the CAD model to be sculpted
2. Generation of the tool path for the cutting tool to follow
3. Conversion of tool path data to native robot language
4. Setup and implementation

Section 3.4.2.1 explains the detail of step 1, section 3.4.2.2 explains the detail of steps 2 – 3 and section 3.4.2.3 covers step 4.

3.4.2.1 CAD Model

The CAD models were modelled using SolidWorks 2003 Educational Edition (see Appendix A.1 for SolidWorks brochure). The 2003 Educational Edition was used since it was the only version compatible with the department's single licence of RobotWorks (explained in the ensuing section). The CAD models were limited to surfaces of low local complexity modelled on the top face of a rectangular slab approximately 160 x 190 x 50 mm in size. The models used for the initial tests were produced by 'lofting' between two profiles separated by a specified distance (160 mm for most trials). Later tests used more complex geometry created in SolidWorks using built in CAD functions and 3D scanner data from the scanning of freeform surfaces (see section 3.5). Figure 3.4-1 shows the aforementioned lofting process in SolidWorks. The particular geometry was chosen for the following reasons:

- Easy to mount.
- Contains both concave and convex surface regions.
- Freeform continuous curves that do not challenge the robot's ability to maintain constant velocities and smooth orientation changes.
- Can be sculpted from blocks of stock sized polystyrene.

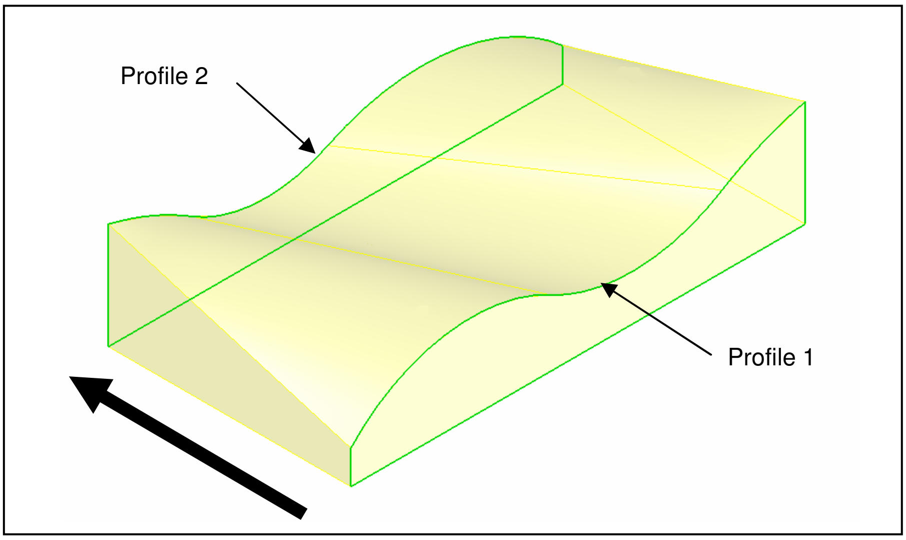


Figure 3.4-1 – 'Lofting' to create CAD model with 3D surface

3.4.2.2 Tool Path Generation and RobotWorks

RobotWorks (see Appendix A.3 for RobotWorks brochure) is an innovative offline robot programming and simulation package which works directly with SolidWorks CAD models. The licence for the package includes a fully functional assembled CAD model of a robot (the KUKA KR6/2 in our case) and a kinematics file containing robot specific information such as joint limit values. The CAD model of the robot, the tool and object to be sculpted are manipulated by RobotWorks all within a SolidWorks 'assembly'. The following steps were taken to produce a programmed robot tool path to sculpt the freeform surfaces.

1. The CAD model of the object to be sculpted was orientated and located within the SolidWorks assembly.

2. The cutting tool was mounted on the mounting flange of the robot using 'mates' within the SolidWorks assembly. The tool had to posses certain features to be correctly recognised and mounted by RobotWorks. These features included an origin at the tool centre point and a hole on the mounting flange of the tool which was to be aligned with a corresponding hole on the mounting flange of the robot.

3. The robots' kinematics file was loaded.

4. Geometric features of the object were selected for the tool to follow. Features were generally a 3D curve which had already been generated on the surface to be sculpted (see explanation and figures 3.4-2 – 3.4-3 below). Features such as edges, flat faces and vertices could also be selected for the tool to follow.

   RobotWorks is typically used to create relatively simple robot paths for applications such as; seam welding, spot welding and spray painting amongst other automated operations. Generating uniformly spaced tool paths for the foam sculpting application was substantially more complex. As previously mentioned 3D curves were used for the tool to follow. These had to be created manually within the SolidWorks CAD file of the object. They were created by projecting a 2D sketch of the desired tool path on to the 3D surface to be sculpted. Figure 3.4-2 shows the sketch projection process. RobotWorks required the projected sketch to be a single continuous entity.

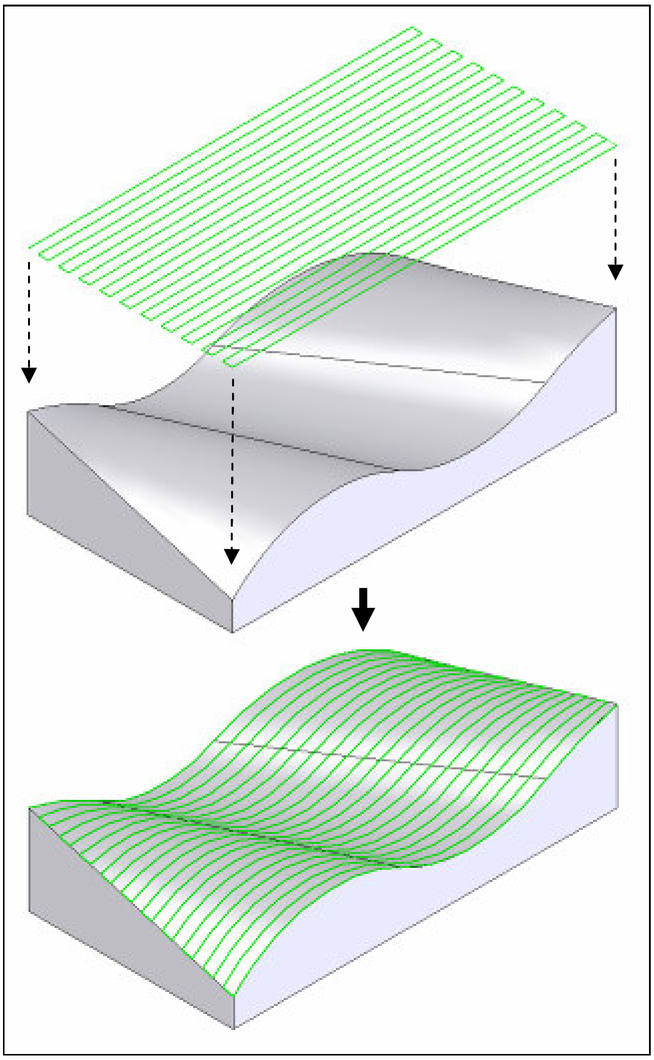
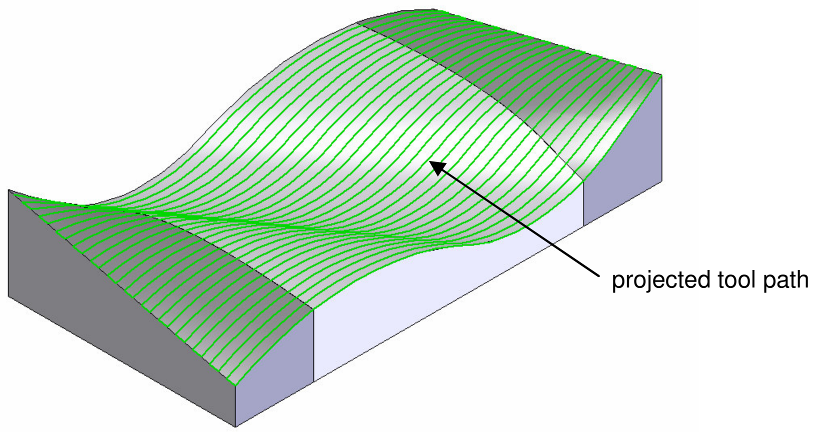


Figure 3.4-2 - Projecting a sketch onto the surface to create a 3D curve

The direction of the tool path and the spacing between successive passes was defined by the 2D sketch. The spacing was chosen according to the size of the tool used and the desired overlap between successive passes. Unlike a CNC router, the heated sculpting tool could not be allowed to pause during cutting because it would continue to melt the surrounding foam, creating substantial surface imperfections. RobotWorks creates tool paths by traversing the tool along the 3D curve in a manner which keeps the tool both normal to the surface it is tracing and the direction in which it is travelling. As previously mentioned, the path was a single entity which meant that the tool was forced to perform physical 'U-turns' at the end of each pass. This issue necessitated the incorporation of a dedicated 'turn around' area so the edges of the model would not be destroyed by over melting during the manoeuvre. The surface of the CAD model was therefore extended further than the actual model to be sculpted to accommodate adequate turn around area at either end of the pass. The tool would then perform its cutting on the foam blank and would turn around for the next pass well clear of the foam. Figure 3.4-3 explains the aforementioned solution.



N.B. The actual object to be sculpted is shown in light grey colour. The CAD model extensions to accommodate tool turn around at the end of each pass are shown in dark grey colour.

Figure 3.4-3 - CAD model extensions to accommodate tool turn around

5. Once the 3D curve was selected, RobotWorks converts it into a tool path. The created tool paths consist of discrete points, each defined by six degrees of freedom. Six degrees are needed since RobotWorks generates paths which cause the tool to be both normal to the surface it traverses and normal to the direction it is travelling. Figure 3.4-4 shows the cutting tool traversing an arbitrary path projected on a free-form surface. Note how the tool remains both normal to the surface and also to the direction it is travelling. The level of point discretization on the tool path can be specified within RobotWorks. More points imply better accuracy.

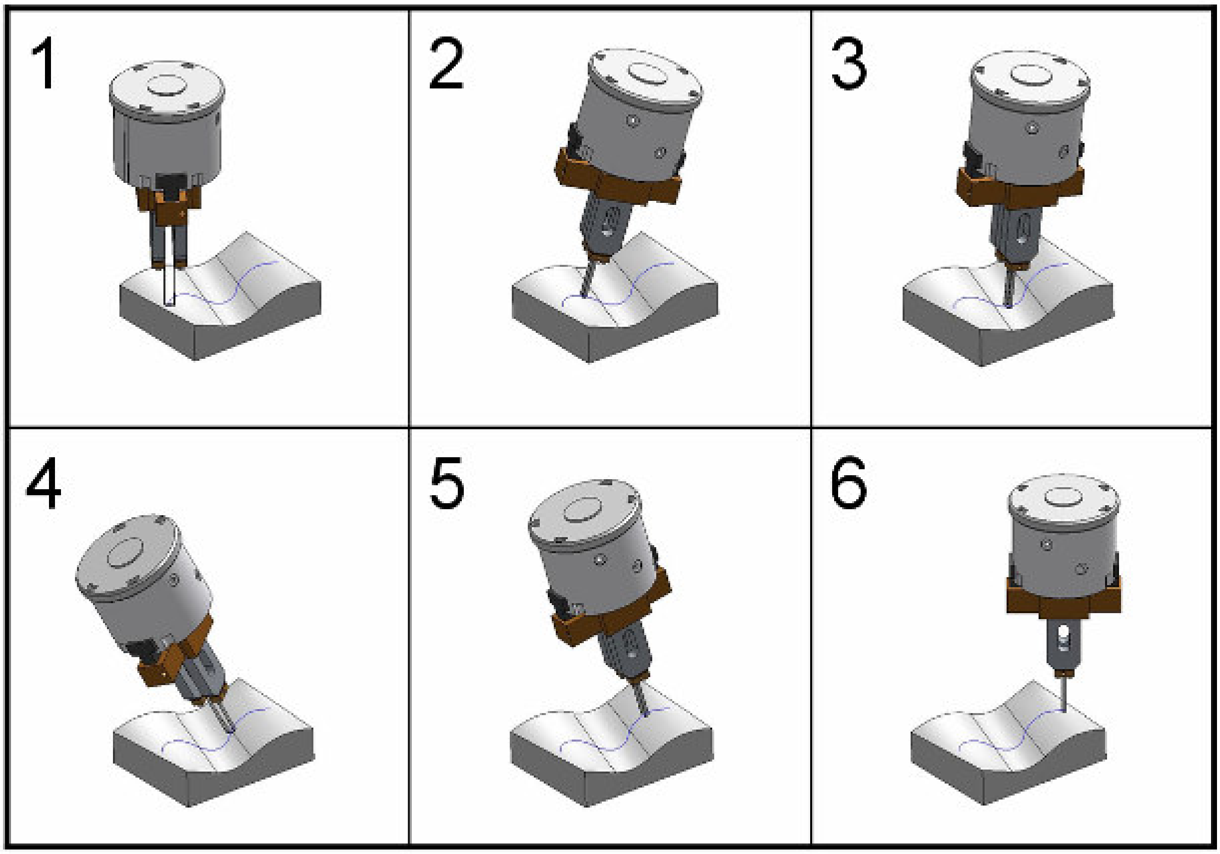


Figure 3.4-4 - Tool orientation by RobotWorks

6. RobotWorks then simulated the motion of the tool traversing the path. This was done dynamically on screen with the tool attached to the robot. During this step, the robot's joint limits were monitored to ensure all points along the path were within reach of the robot. In addition, collisions between the tool, work piece, robot linkages and setup fixtures could be dynamically monitored and checked. Of primary importance was the need to check there were no collisions between the tool (less the blade) and the work piece. It was also possible to overlay the foam blank and check for collisions between the tool (less the blade) and un-cut material. This is illustrated in figure 3.4-5. The figure shows a 'screen print' of the SolidWorks/RobotWorks working environment during a path simulation and collision detection check. At the time of the screen print, the programs were in the process of running the tool along a defined path (TCP trail visible). The object being sculpted has been hidden to improve clarity. As shown in the user-form entitled 'Setup Interference', the tool (less the blade) has been selected as the 'moving part' while the blank has been selected as the 'fixed part'. The user-form entitled 'RobotWorks' contains the main controls for the RobotWorks program, while the user-form below it entitled 'Control Pad' shows the position value for all of the robot's 6 axes. The simulation is automatically paused when any one of the axis limits are exceeded.

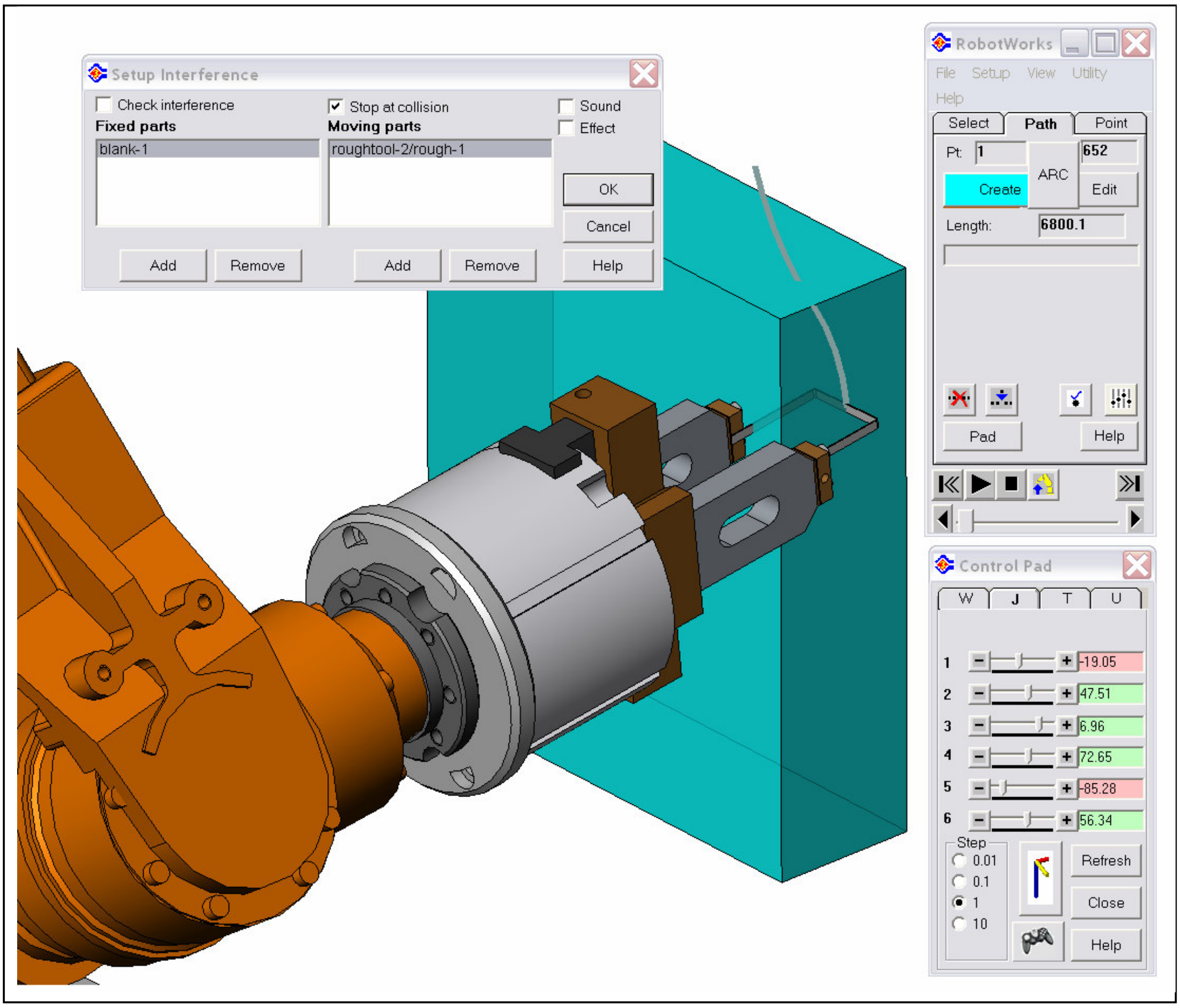


Figure 3.4-5 - Collision detection and axis limit check in RobotWorks

7. Once a successful simulation had been run, the points were converted into the native KUKA language. Figure 3.4-6 shows an excerpt from a typical KUKA control program. The first line of code shown defines the tool. The six coordinates given (x, y, z, A, B, C) simply define the TCP with respect to a default coordinate system located at the centre of the mounting flange. The next line defines the base coordinate system. The six coordinates given define the location of the base coordinate system with respect to the robot coordinate system. For example, {x 0, y 0, z 0, A 0, B 0, C 0} would result in the base coordinate system being coincident with the robot coordinate system. The lines of code prefixed by 'LIN' represent single points on the tool path which are linearly interpolated between by the tool. Typical tool paths for the preliminary trials contained between 200 and 500 points.

```
$TOOL={X 0.000,Y 0.000,Z 187.000,A -0.069,B 0.000,C 0.000}

$BASE={X 1014.233,Y 687.927,Z 787.380,A 0.000,B 0.000,C 0.000}

PTP  {X 157.593,Y -24.627,Z 47.399,A 89.938,B 51.717,C 11.053} C_PTP

HALT

$VEL_AXIS[1]=100
$VEL_AXIS[2]=100
$VEL_AXIS[3]=100
$VEL_AXIS[4]=100
$VEL_AXIS[5]=100
$VEL_AXIS[6]=100

$ACC_AXIS[1]=100
$ACC_AXIS[2]=100
$ACC_AXIS[3]=100
$ACC_AXIS[4]=100
$ACC_AXIS[5]=100
$ACC_AXIS[6]=100

LIN  {X 157.593,Y -24.627,Z 47.399,A 89.938,B 51.717,C 11.053} C_DIS
LIN  {X 158.625,Y -22.072,Z 43.882,A 90.000,B 52.116,C 6.315} C_DIS
LIN  {X 159.649,Y -19.474,Z 40.402,A 90.000,B 52.523,C 1.610} C_DIS
LIN  {X 160.626,Y -16.835,Z 36.952,A 90.000,B 52.930,C -2.870} C_DIS
LIN  {X 161.523,Y -14.166,Z 33.523,A 90.000,B 53.337,C -6.999} C_DIS
LIN  {X 162.317,Y -11.485,Z 30.101,A 90.000,B 53.744,C -10.682} C_DIS
```

Tool and base coordinate system definitions

Commands the robot to move to the first point of the path from its home position

Defining maximum axis velocities and accelerations (% of max limit)

Each line of code represents a fully defined point on the tool path

Figure 3.4-6 - Excerpt from a KUKA control program

Because the nichrome cutting elements were rather delicate and could be bent easily if the cutting force got too high, the depth of cut was generally limited to approximately 20 mm. This necessitated the use of a 'roughing pass' followed by a 'finishing pass'. The roughing pass by and large was achieved with a 25 mm wide cutter applied to a path with spacing between successive passes of 20 mm. The roughing pass was generally accomplished at high feed rates and temperatures and would leave 10 – 12 mm of material for the finishing pass to remove. For the trials which utilized both roughing and finishing passes, two separate tool paths were generated. Figure 3.4-7 below shows a typical roughing and finishing path.

It should be noted that the roughing pass is offset from the final surface by altering the 'z' coordinate of the tool definition in the control program.

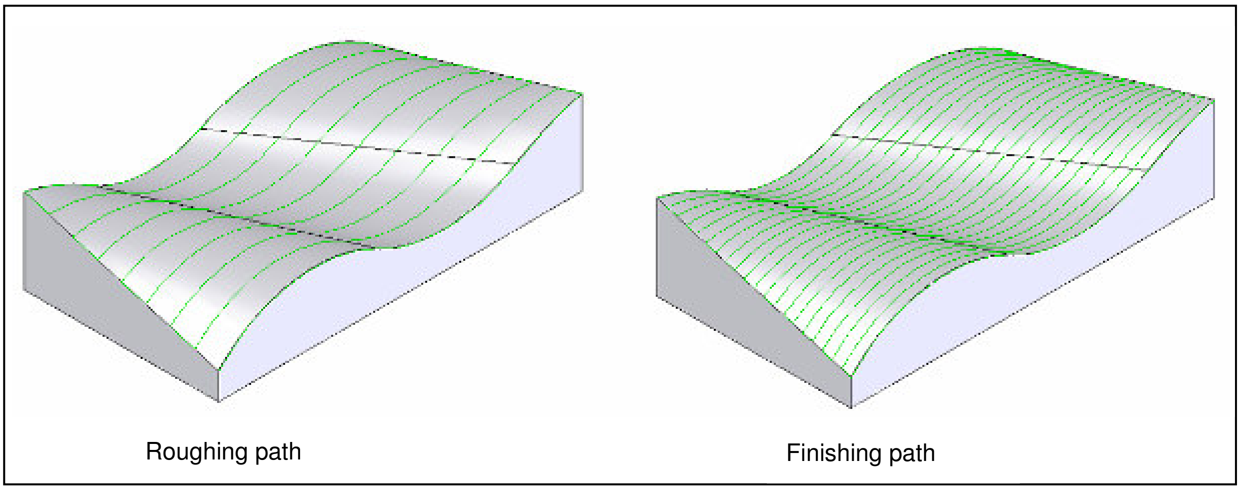


Figure 3.4-7 - Roughing and finishing paths

3.4.2.3 Robot Setup and Program Execution

In order to efficiently transfer the generated control program to the robot's control PC, a code template was used. The template included pre-written code to define robot velocities, coordinate systems, and 'return to home' speeds and motions. The code generated by RobotWorks was simply copied and pasted into the template. The following steps were then followed to set up the equipment and execute the program.

1. The prepared control program was transferred to the control PC via a 3.5" floppy disk.
2. To ensure no surprises, the program was first executed in free air at 30% velocity with no foam blank mounted.
3. Provided the program ran as intended, the foam blank was then referenced and mounted. To aid in the referencing of the foam blank, the base coordinate system was programmed in RobotWorks to the top left corner of the blank. The foam blank was temporarily mounted and the robot was commanded to go to the top left corner of the blank with the command: 'PTP {X 0, Y 0, Z 0, A 0, B 0, C -90}'. If the tool tip did not align with the top left corner of the blank, the table and/or blank were manually moved into position. The tool was then traversed around the perimeter of the front face of the blank to check alignment in all planes. Once the correct alignment was confirmed the blank was secured in place via four coarse screws which gripped the sides of the blank.
4. The DC power supply was then turned on and the current was adjusted via the manual rotary switch. For the preliminary trials, the current level was set based on past cutting experience and feel (a piece of foam was run through the heated blade by hand).
5. An extractor fan to remove the fumes was switched on and the control programs were executed. For the majority of the finishing passes, the swarf was removed by hand following each pass.

3.4.3 Results and Discussion

The following results were generated from twelve distinct cutting trials. Each trial was performed on a 160 x 190 x 40 (or 50) mm block of EPS or XPS. Observations from the trials were used to progressively develop and change the testing conditions (input CAD geometry, cutting speed, blade size, blade profile, temperature and path spacing). The results are presented in chronological order and should be viewed as an evolutionary journey of understanding. For each of the twelve trials, the following data was recorded:

- _Tool velocity:_ this was the velocity of the TCP with respect to the foam object used for the finishing path. It was defined in the robot's control program and measured in ms^{-1}. It should be noted that during initial trials the robot's velocity seemed to be limited (i.e. increasing the velocity in the control program seemed to have no effect). It was initially thought that the control PC was having trouble reading the lines of code in the control programs fast enough. It was later found that the velocity was being limited by the default maximum settings for axis velocities. Once increased, the robot's velocity appeared unlimited and the motion was visibly smoother. Trials 1 – 6 were subsequently performed under dubious velocity commands.
- _Blade profile:_ two blade profiles were used, namely; ball nose and square .
- _Blade size:_ various blade sizes were used. The value when stated refers to either the diameter of the bull nose blade or the length of the flat section of the square blade and was measured in mm.
- _Path type:_ for the first nine trials, simple parallel bi-directional paths, , were used. The final four trials experimented with a unidirectional path, .
- _Path spacing:_ this was the distance between adjacent passes. For example, a path spacing of 6 mm traversed with an 8 mm square-ended tool would give rise to an overlap of 2 mm.
- _Rough cutting time:_ this was the machine time taken to complete the rough cutting sequence (if a rough cutting sequence was used) and was measured in seconds.
- _Finish cutting time:_ this was the machine time taken to complete the finish cutting sequence and was measured in seconds.
- _Total machine time:_ this was the total machine time (rough cutting time + finish cutting time) and was measured in seconds.

In addition to the data recorded, observations were made and are reported along with two photographs of each cut sample (an overall view and a close-up view).

To indicate which particular testing attribute has been changed from the previous test, an asterix (*) is located in front of the changed attribute in the test's data table.

3.4.3.1 Trial 1

Trial 1 represents the first attempt at robotic 3D sculpting. The model to be sculpted was arbitrary and was simply created by lofting between two profiles as previously explained. The conditions for the test along with the times taken are shown in table 3.4-1 below.

Table 3.4-1 - Trial 1 data

Attribute	Value
Tool velocity	0.05 ms^{-1} (inaccurate)
Blade profile	
Blade size	25 mm
Path type	
Path spacing	12 mm
Rough cutting time taken	N/A
Finish cutting time taken	90 seconds
Total machine time	90 seconds

Figures 3.4-8 and 3.4-9 show an overall photo of the cut sample and a close-up shot respectively.

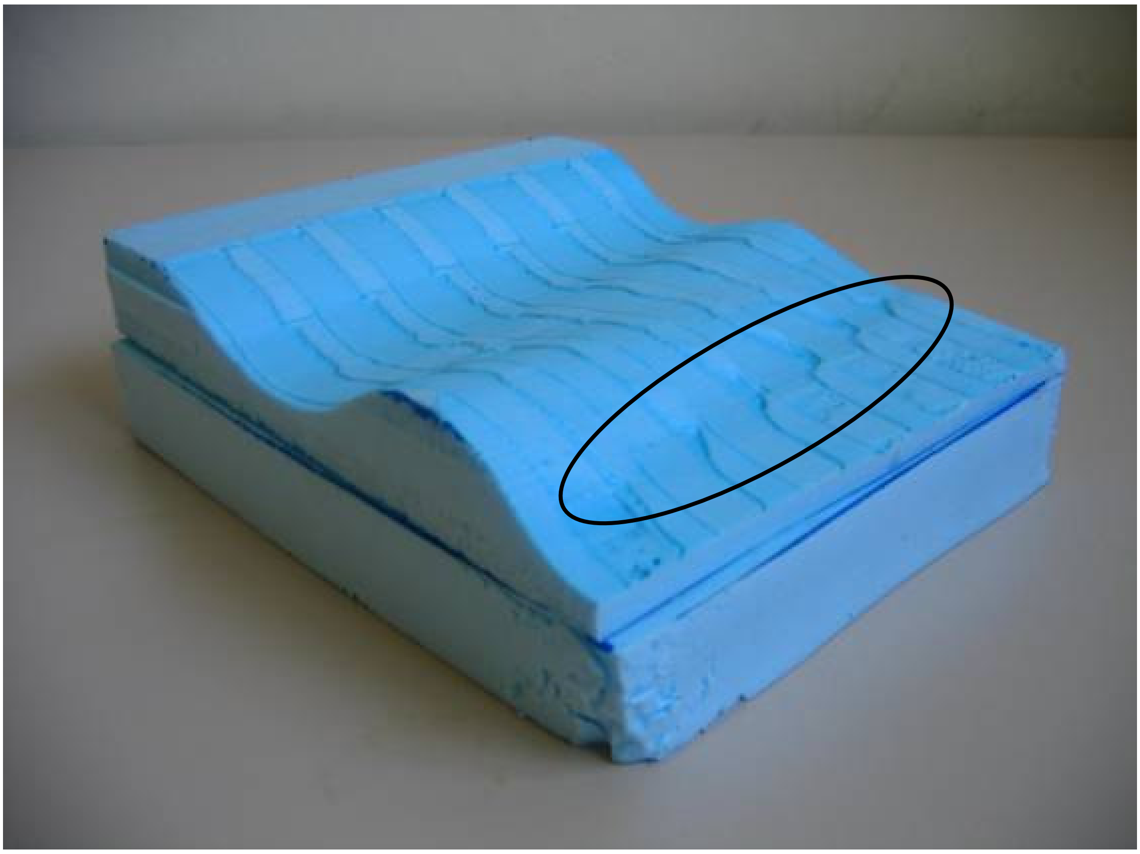


Figure 3.4-8 - Trial 1 overall photograph

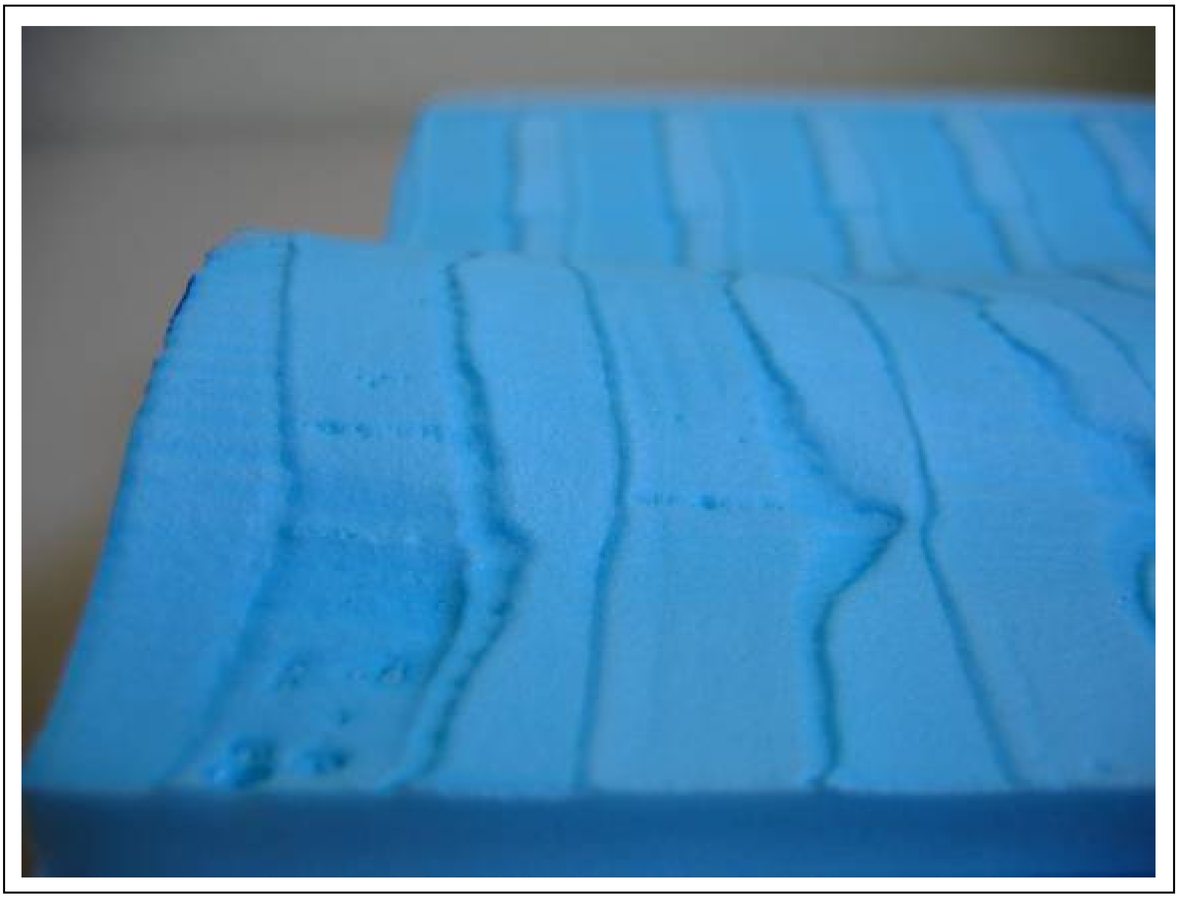


Figure 3.4-9 - Trial 1 close-up photograph

The following observations were made regarding the cut sample from trial 1:

- The cutting mechanism seemed to be predominately thermal (as opposed to mechanical). This is evident in the smoothed 'iced cake' appearance shown in figures 3.4-8 and 3.4-9. The effect is caused by the temperature being too high relative to the feed rate or the feed rate being too low relative to the temperature.
- The overlap between successive passes appears rather lumpy and non-linear. This is caused by an excessive overlap (approximately 12 mm) where the tool passes over previously cut regions and re-melts the material. Despite the non-linearity, the overlap ridge created is almost identical for each overlap (i.e. parallel irregular lines).
- As indicated by the black ring on figure 3.4-8, there is a region which had excessively deep melted pockets. These were created by a process known as gouging, where the tool width is too large for the local curvature to be sculpted. The TCP follows the cutter path while the corners of the tool gouge into the surface which has already been cut.

The sculpted object had both concave and convex surfaces yet the changes in geometry were too irregular to observe patterns and effects caused by the established cutting mechanics. This necessitated the modification of the CAD model for the next trial. Additionally, it was decided to reduce the cutting temperature and trial a ball nose cutter with a reduced path spacing to avoid the aforementioned overlap and gouging issues.

3.4.3.2 Trial 2

Trial 2 used a modified CAD model which again, was created by lofting between two profiles. The new model contained relatively equal amounts of concave and convex surface regions and was more regular than the model used for trial 1. The conditions for the test along with the times taken are shown in table 3.4-2 below.

Table 3.4-2 - Trial 2 data

Attribute	Value
Tool velocity	0.05 ms^{-1} (inaccurate)
*Blade profile	
Blade size	25 mm
*Path type	
Path spacing	8 mm
Rough cutting time taken	N/A
Finish cutting time taken	136 seconds
Total machine time	136 seconds

Figures 3.4-10 and 3.4-11 show an overall photo of the cut sample and a close-up shot respectively.

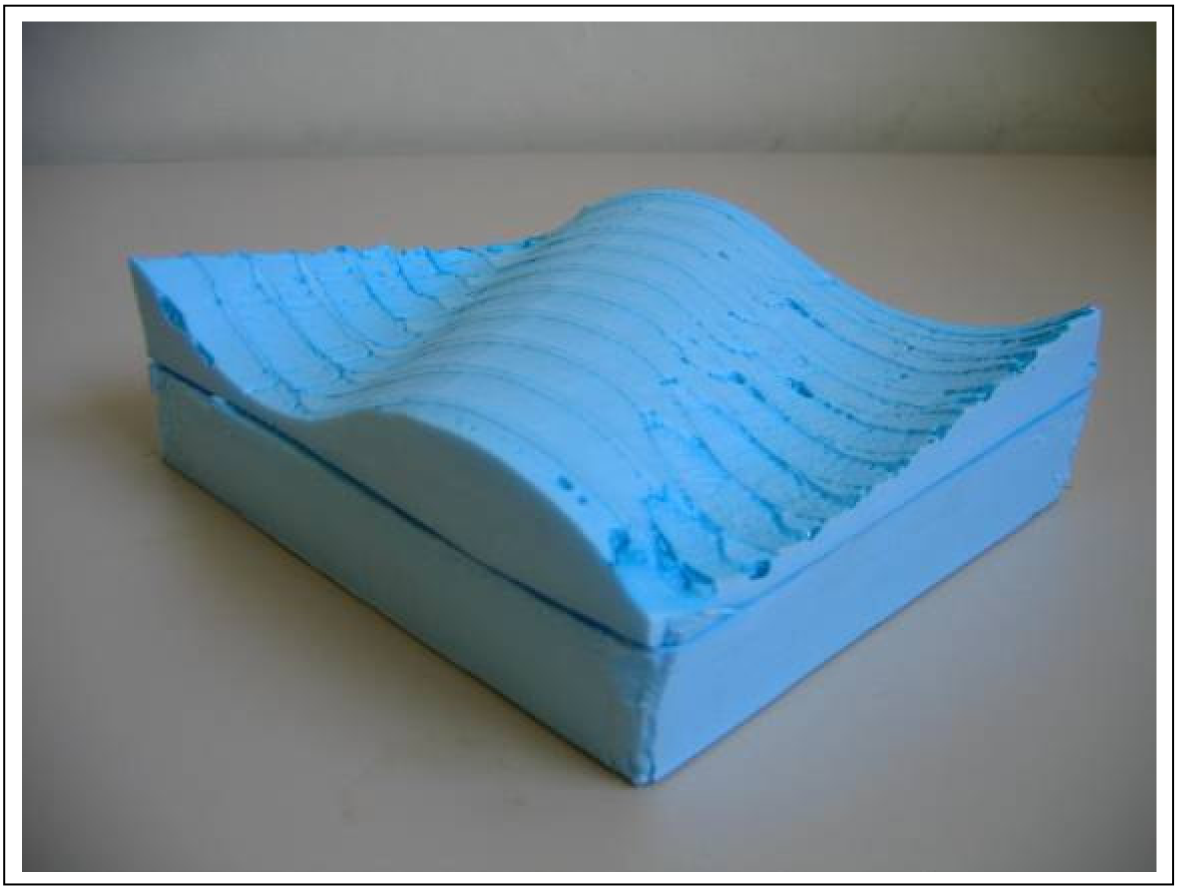


Figure 3.4-10 - Trial 2 overall photograph

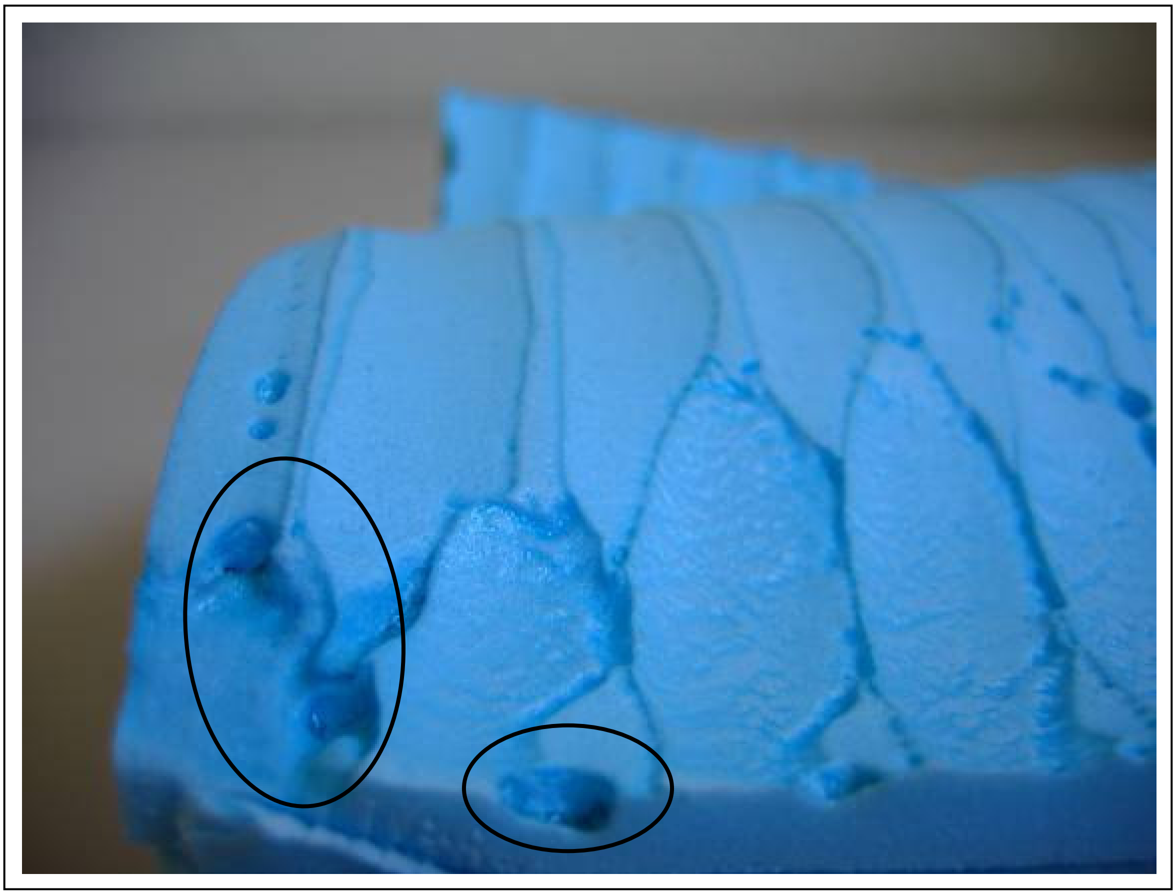


Figure 3.4-11 - Trial 2 close-up photograph

The following observations were made regarding the cut sample from trial 2:

- As shown in figures 3.4-10 and 3.4-11, the surface appears very cusped. This is clearly a function of the tool shape and the path spacing used for the trial.
- When looking down on the sample from above, the parallel lines caused by cutter are not straight but are wavy. This is caused by the fact that the tool angles over to maintain a normal angle with the surface it is sculpting. In doing so the tool's points of contact with the foam vary. If the sculpting process used only 3-axis control, the parallel lines created by the tool would be expected to be straight.
- Convex regions of the sample's surface appear more defect free than the concave regions. Defects take the form of small holes or lines which appear to have been created by the depositing of molten material on the surface which subsequently sinks into the surface. A possible explanation for the cleaner convex surface is as follows. When sculpting convex surfaces, the tool's direction of travel vector is pointing away from the surface it is cutting. When sculpting concave surfaces, the vector is pointing into the surface it is cutting. Consequentially, the force exerted on the foam during convex sculpting is directed away from the foam compared to into the foam for concave sculpting. It is postulated that these factors play a key role in determining the cleanness of the sculpted surface.
- As indicated by the black rings on figure 3.4-11, large imperfections were present at either end of the foam where the tool entered and exited the foam. The primary cause of these large defects was related to the surface geometry at either end of the sample combined with the size of the tool

and the size of the area designated for turning around outside either end of the sample. Because the turning around area was too tight with regard to the local surface geometry and the size of the tool, a portion of the tool hovered over the already cut surface during the turning manoeuvre. This resulted in excessive melting of the material at selected locations along the edges of the sample.

Due to the tool turn around issues and the fact that the focus should be biased towards the sculpting of concave surfaces (since these seemed to be exhibiting the most unusual effects), it was decided that the CAD model be modified in the future. Furthermore it was hypothesized that, a second cutting pass 90º opposed to the first pass would remove the highly cusped surface finish.

3.4.3.3 Trial 3

Trial 3 was essentially the same as trial 2 except it comprised a second finishing pass which was 90º opposed to the first pass. This was aimed at removing the cusped surface finish exhibited in trial 2. The conditions for the test along with the times taken are shown in table 3.4-3 below.

Table 3.4-3 - Trial 3 data

Attribute	Value
Tool velocity	0.05 ms^{-1} (inaccurate)
Blade profile	
Blade size	25 mm
*Path type	+
Path spacing	8 mm
1st finishing pass time taken	158 seconds
2nd finishing pass time taken	158 seconds
Total machine time	316 seconds

Figures 3.4-12 and 3.4-13 show an overall photo of the cut sample and a close-up shot respectively.

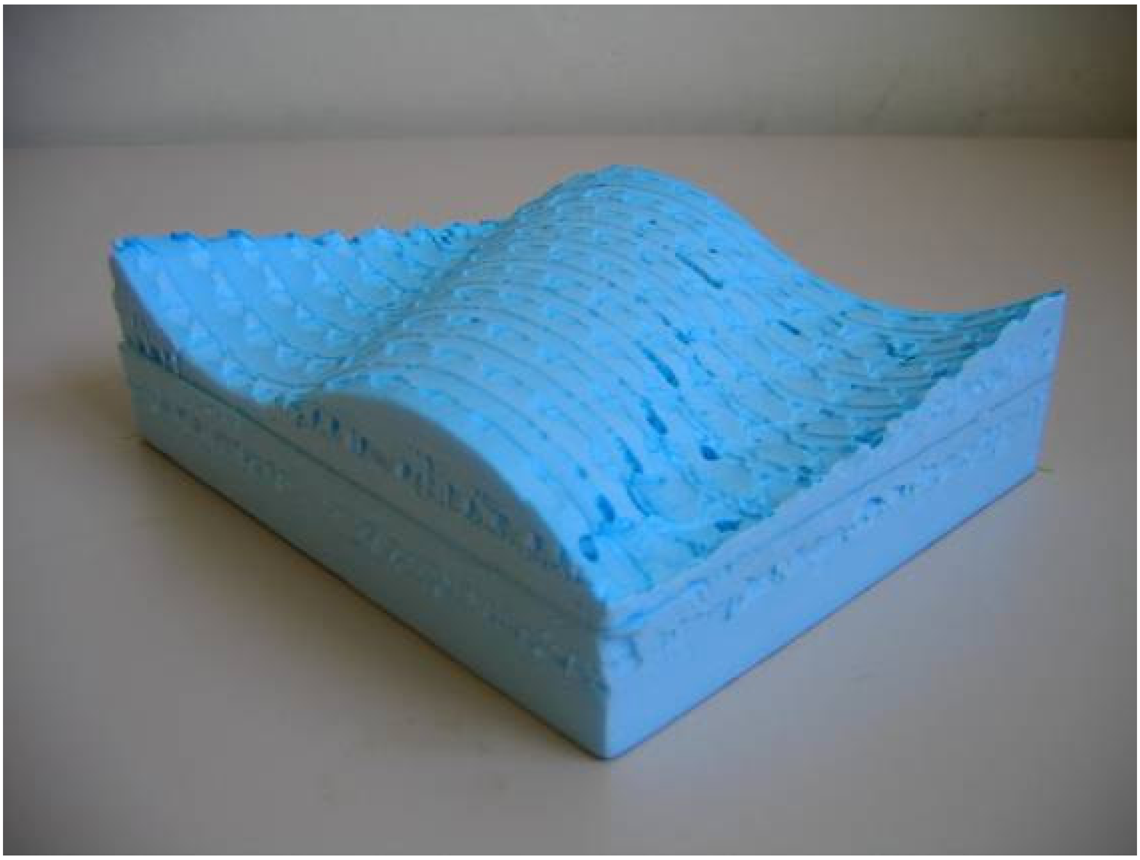


Figure 3.4-12 - Trial 3 overall photograph

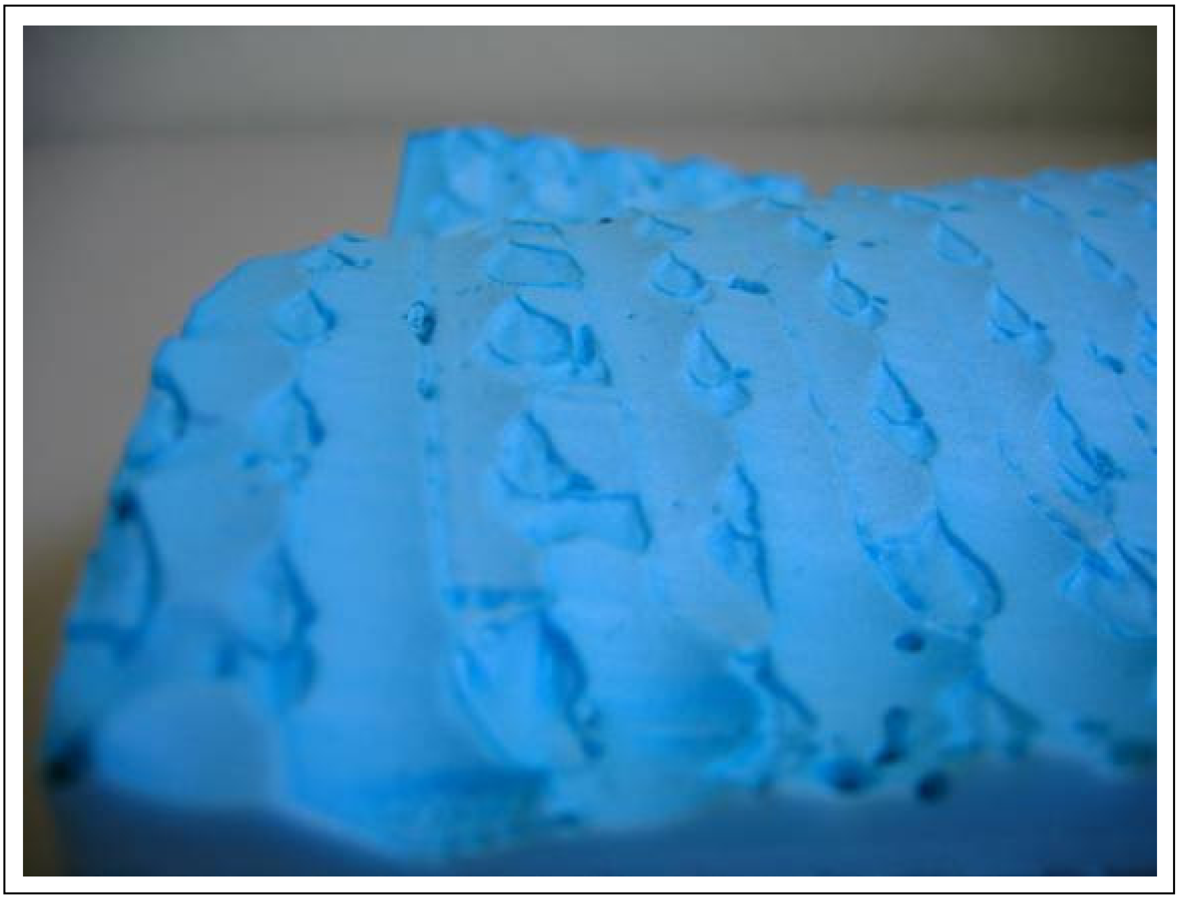


Figure 3.4-13 - Trial 3 close-up photograph

The following observations were made regarding the cut sample from trial 3:

- The first pass gave identical results to the sample produced in trial 2. The second finishing pass which aimed to remove the cusped surface created an unexpectedly rough 'double cusped' surface. As can be seen in figure 3.4-13 the second pass seemed to only cut the tops off the cusps and leave the bottoms of the dips from the first pass largely untouched.
- The sample also exhibited substantial imperfections created by the depositing of molten material which subsequently melted into the surface creating large holes. These were caused by the second pass, and it is thought they occurred via the following mechanism: The cutting occurring in the second pass was essentially intermittent and shallow (cutting the top off the cusps followed by no cutting in between). Hence, the material was not removed but rather, was completely melted and carried on the blade only to be deposited upon engagement with the next cusp. Although the figures do not show it clearly, there are many such small molten deposits just prior to the topped cusps.
- The surface created by the double finishing pass was substantially harder than the surface created from trial 2. This was caused by the predominantly thermal cutting mechanism prevalent in the second pass which created a hard, brittle melted skin.

The results from this trial proved that a second pass 90º opposed to the first made the surface finish worse. It was also decided that the CAD model ought to be changed to rectify the edge melting caused by insufficient turn around area.

3.4.3.4 Trial 4

Trial 4 used a modified CAD model which was essentially the inverse of the model used for trials 2 - 3. The model exhibited a larger concave region through the centre with smaller convex regions and extended turn around areas at either end. With the introduction of a new model, the first test was rather exploratory in nature; hence a large tool and path spacing were used. The conditions for the test along with the times taken are shown in table 3.4-4 below.

Table 3.4-4 - Trial 4 data

Attribute	Value
Tool velocity	0.05 ms^{-1} (inaccurate)
*Blade profile	
Blade size	25 mm
*Path type	
*Path spacing	16 mm
Rough cutting time taken	N/A
Finish cutting time taken	77 seconds
Total machine time	77 seconds

Figures 3.4-14 and 3.4-15 show an overall photo of the cut sample and a close-up shot respectively.

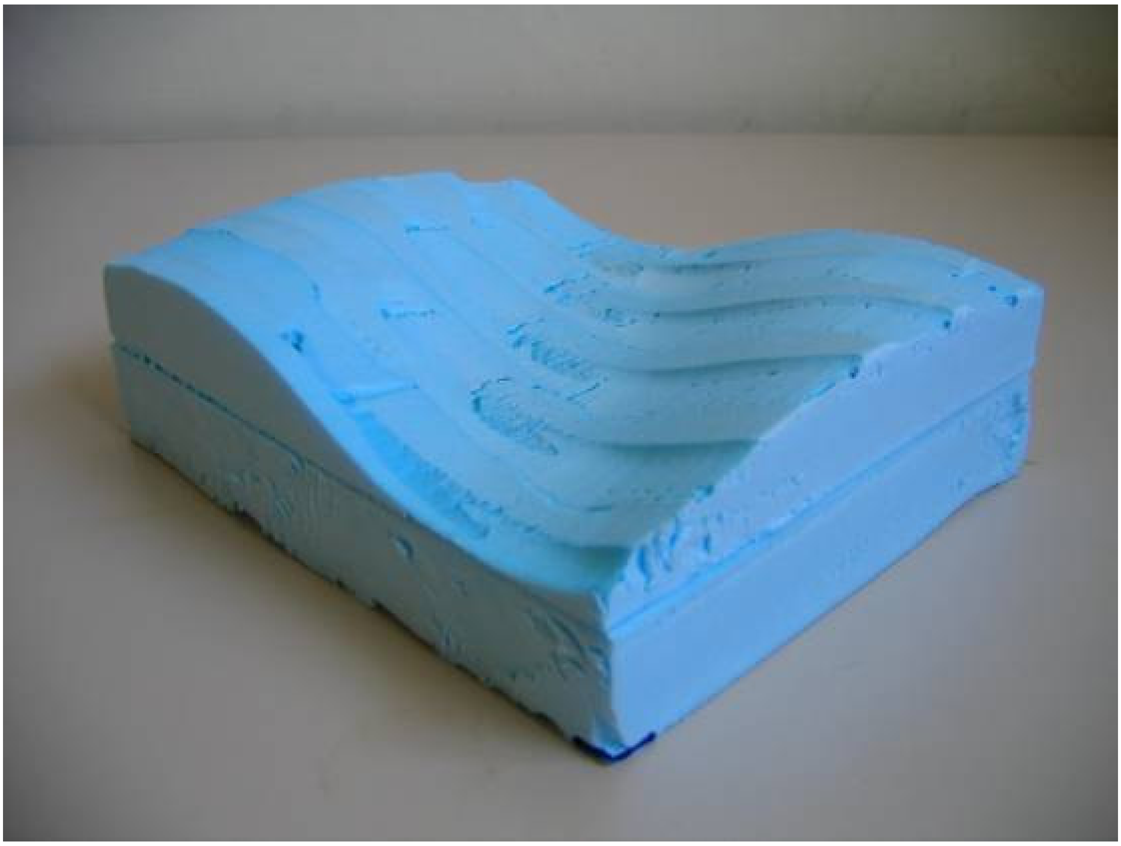


Figure 3.4-14 - Trial 4 overall photograph

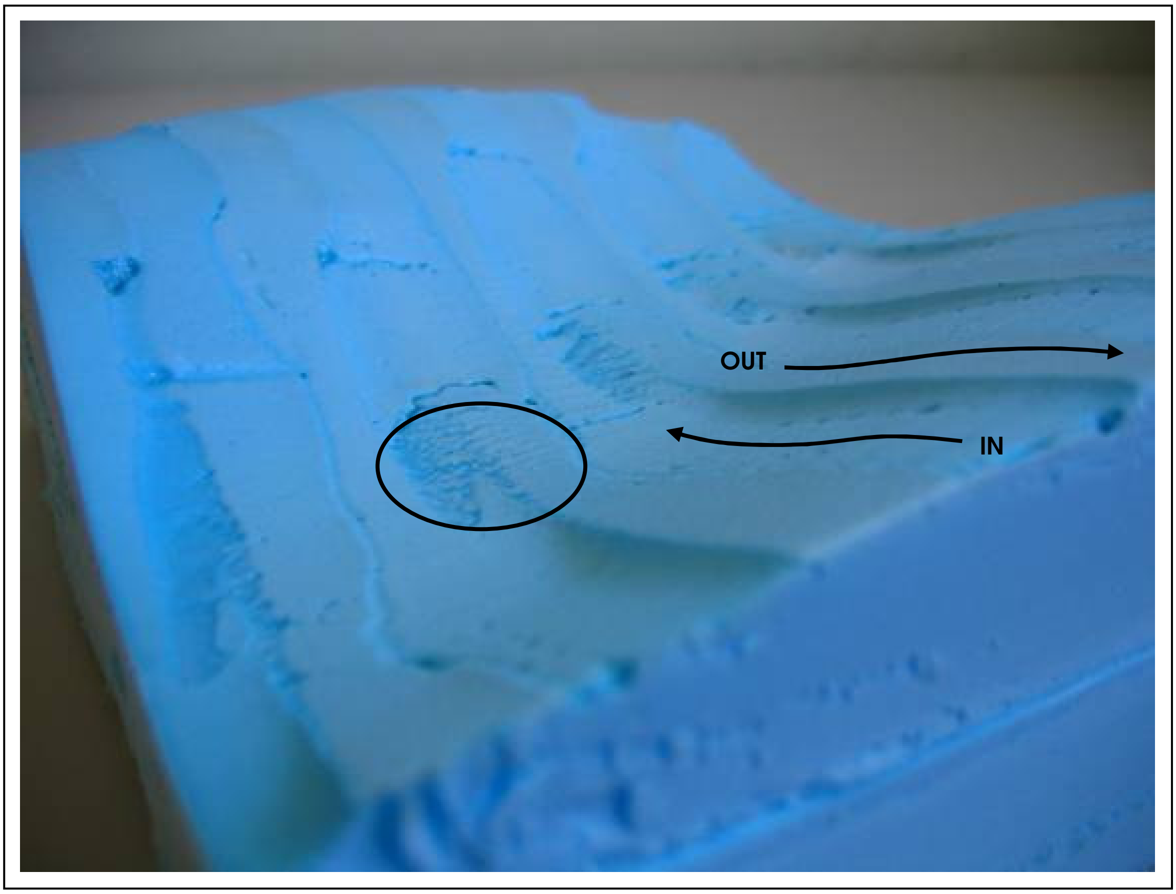


Figure 3.4-15 - Trial 4 close-up photograph

The following observations were made regarding the cut sample from trial 4:

- The most striking observation from the sample was the alternating high and low surface strips. This was the first indication of substantial tool temperature variation. When the tool enters the foam it is relatively hot, as the cut progresses the temperature drops significantly. The arrows in figure 3.4-15 show the stark effects of the difference in blade temperature between the beginning of a pass ('IN') and the end of a pass ('OUT'). Observably, a hotter tool removes more material than a cooler tool hence producing the alternating high/low surface finish.
- As indicated by the black ring in figure 3.4-15, the surface exhibited some unusual transverse striations which predominantly appeared in the regions where the tool was nearing the end of the pass (i.e. tool nearing its coldest point). It is understood that the striations were caused due to the tool being too cold with respect to the feed rate or the feed rate being too fast with respect to the temperature. Under such conditions the cutting mechanism is primarily mechanical and the foam is subsequently 'ripped' as opposed to 'cut'.

Trial 4 proved that although the surface finish was inadequate for a finishing operation, the use of a large tool and large path spacing could be employed for some sort of rough cutting strategy, especially considering the time in which all the material was removed (77 seconds). It was first decided however, that finer path spacing be trialled with a large bull nose tool.

3.4.3.5 Trial 5

Trial 5 was essentially the same as trial 2 except for the CAD model used. It was expected that the changed geometry would better show the effects of the various cutting mechanics in action. The conditions for the test along with the times taken are shown in table 3.4-5 below.

Table 3.4-5 - Trial 5 data

Attribute	Value
Tool velocity	0.05 ms^{-1} (inaccurate)
*Blade profile	
Blade size	25 mm
Path type	
*Path spacing	8 mm
Rough cutting time taken	N/A
Finish cutting time taken	154 seconds
Total machine time	154 seconds

Figures 3.4-16 and 3.4-17 show an overall photo of the cut sample and a close-up shot respectively.

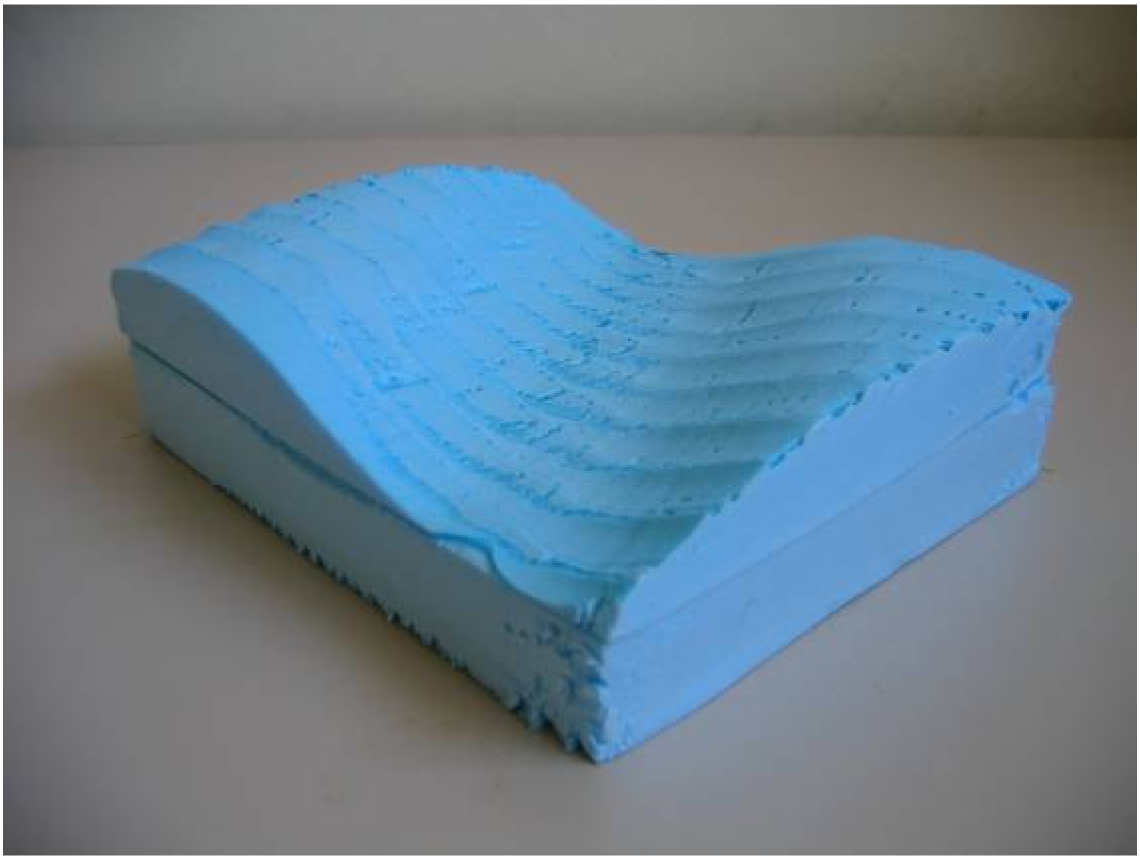


Figure 3.4-16 - Trial 5 overall photograph

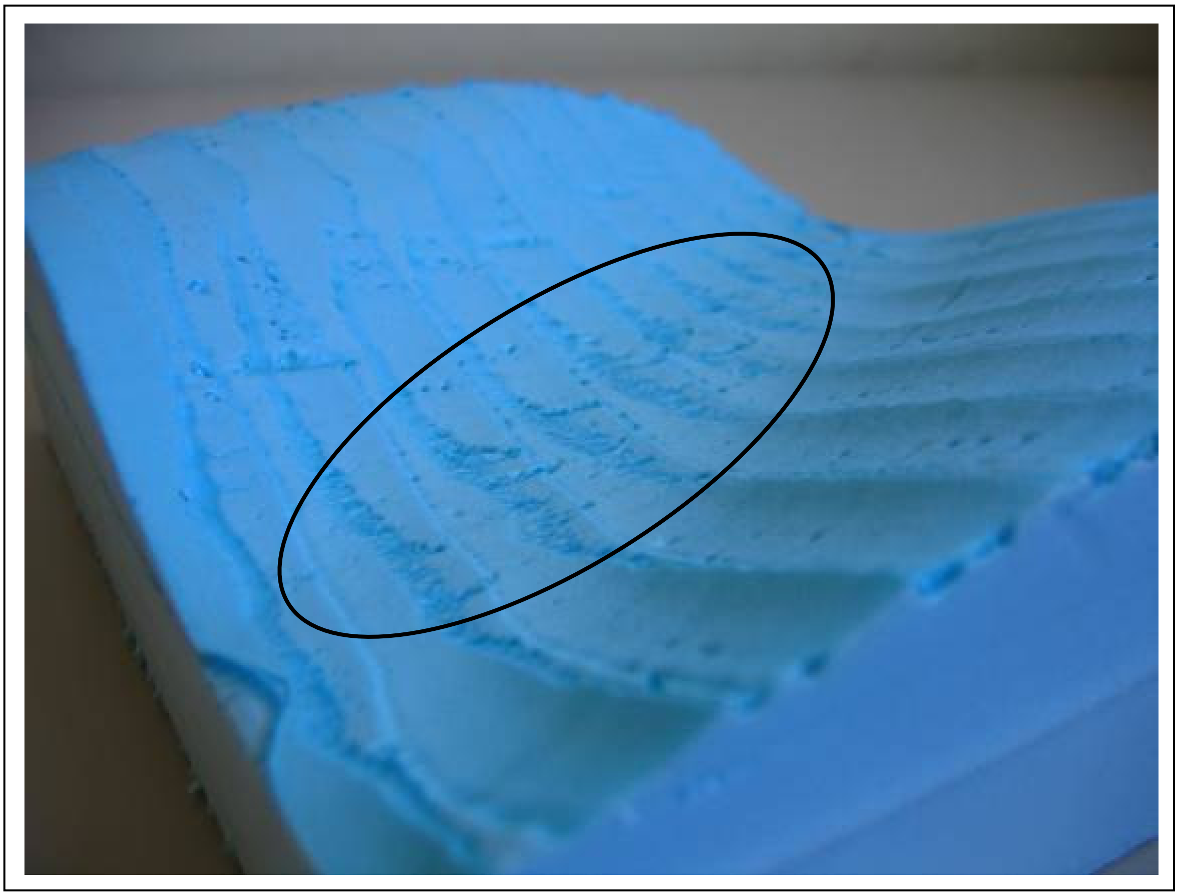


Figure 3.4-17 - Trial 5 close-up photograph

The following observations were made regarding the cut sample from trial 5:

- As shown in figures 3.4-16 and 3.4-17, the surface appears very cusped. This is clearly a function of the tool shape and the path spacing used for the trial.
- As indicated by the black ring in figure 3.4-17, a substantial amount of over-melting occurred in the concave portion of the sample. This was partly caused due to the size of the tool with respect to the path spacing used. The reason for the majority of the over-melting occurring in the concave regions has yet to be sufficiently explained (i.e. why not in the convex regions?). A possible contributing factor could be the difference in the direction of the force exerted on the foam when cutting concave and convex surfaces (as explained with trial 2).
- The path spacing used for the trial was set at 8 mm, which implies one should observe a total of 20 individual passes across the 160 mm of the sample's width. The surprising fact however, is that only 10 passes can be counted! Furthermore, the passes which can be distinguished are all consistent with the tool entering the foam (i.e. tool is hotter at entry, hence; deeper cuts with more 'melted' looking surface). It can be surmised from this observation that the hotter entry cuts into the foam cut away any evidence of the cooler exit cuts.

Trial 5 reinforced the idea, that to achieve superior surface finishes, a smaller tool and much reduced path spacing was required.

3.4.3.6 Trial 6

The sixth trial represented the first trial which explored the hypothesis that a smaller tool with reduced path spacing would result in better surface finishes (and would hence be more accurate). The tool chosen for the trial was an 8 mm square profiled tool and was applied to a path with a spacing of 6 mm (i.e. 2 mm of overlap between adjacent passes). The conditions for the test along with the times taken are shown in table 3.4-6 below.

Table 3.4-6 - Trial 6 data

Attribute	Value
*Tool velocity	0.075 ms^{-1} (inaccurate)
*Blade profile	
*Blade size	8 mm
Path type	
*Path spacing	6 mm
Rough cutting time taken	60 seconds
Finish cutting time taken	187 seconds
Total machine time	247 seconds

Figures 3.4-18 and 3.4-19 show an overall photo of the cut sample and a close-up shot respectively.

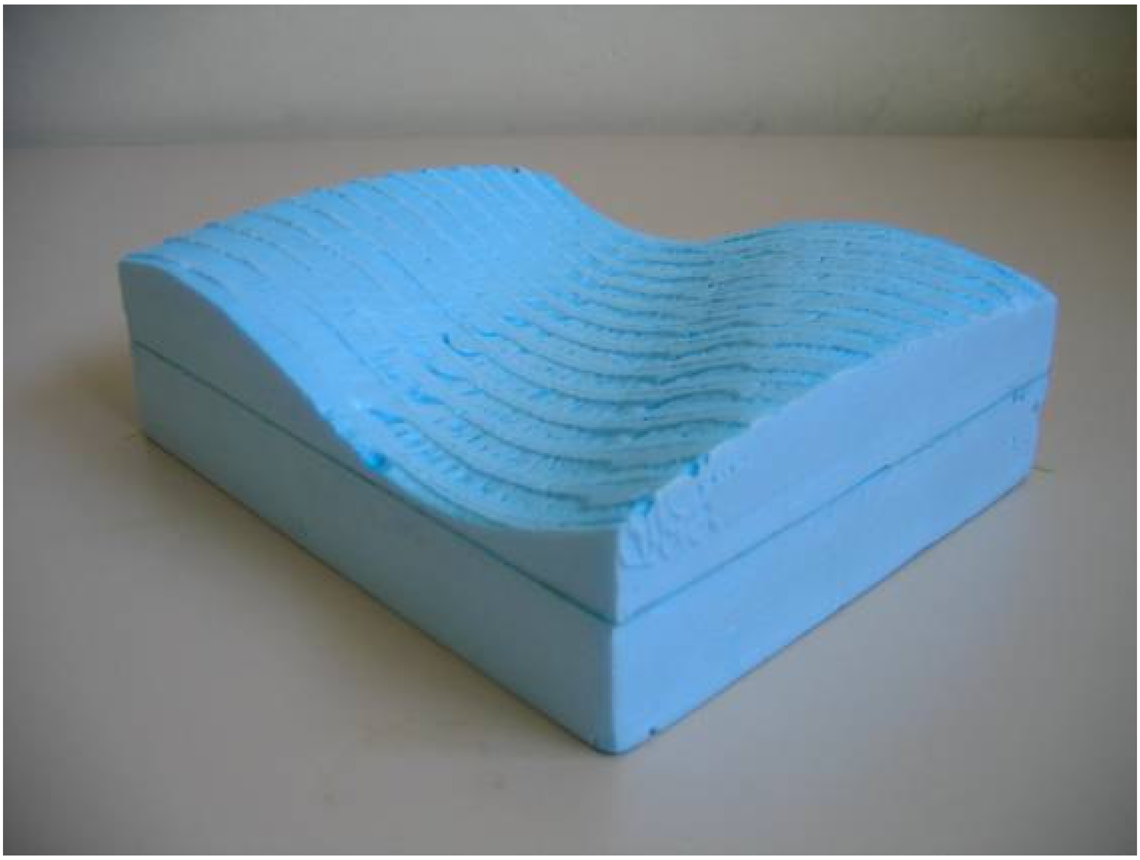


Figure 3.4-18 - Trial 6 overall photograph

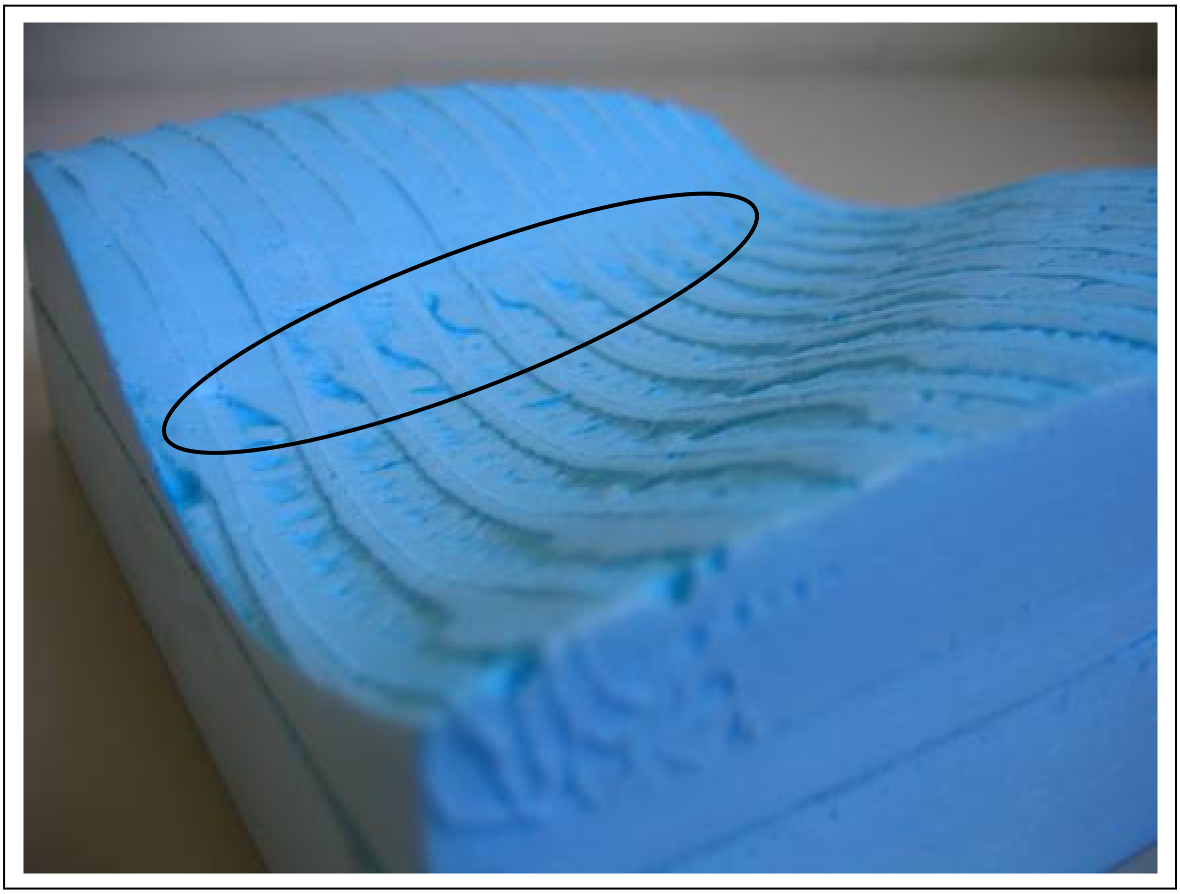


Figure 3.4-19 - Trial 6 close-up photograph

The following observations were made regarding the cut sample from trial 6:

- The surface form created with a smaller tool and reduced path spacing was substantially improved compared with the sample produced from the previous trial. This was as expected, since a smaller tool applied to a denser tool path will produce a surface closer to that of the actual CAD model (the same holds for conventional 3-axis CNC surface milling).
- With a smaller overlap and a square ended tool the temperature variation was clearly observable through the alternating high/low surface profile as can be seen in figure 3.4-19.
- Like the sample produced in trial 5, the sample from this trial also exhibited over-melting in the same region on the sample, as indicated by the black ring on figure 3.4-19. This prompted the thought that the robot's velocity was slower through this section resulting in the over-melting. To test this hypothesis, the robot's velocity was doubled and the program was re-run without any foam in place. Surprisingly there was no noticeable difference in the robots velocity which meant that something was limiting it. Initially it was postulated that the robot's control PC was having trouble reading the lines of code fast enough. However, it transpired that the default maximum axis velocities were too low and were therefore the limiting factor. These were consequently increased in preparation for the next trial.
- One end of the sample seemed to contain more surface defects than the other end, despite the fact that the tool path was bi-directional. This has yet to be explained.

3.4.3.7 Trial 7

Trial 7 was the first trial to be accomplished with the increased maximum robot axis velocities. This allowed the robot to move at the programmed speed throughout the entire cut. The conditions for the test were the same as for trial 6 and are shown below in table 3.4-7.

Table 3.4-7 - Trial 7 data

Attribute	Value
Tool velocity	0.075 ms^{-1}
Blade profile	
Blade size	8 mm
Path type	
Path spacing	6 mm
Rough cutting time taken	45 seconds
Finish cutting time taken	130 seconds
Total machine time	175 seconds

Figures 3.4-20 and 3.4-21 show an overall photo of the cut sample and a close-up shot respectively.

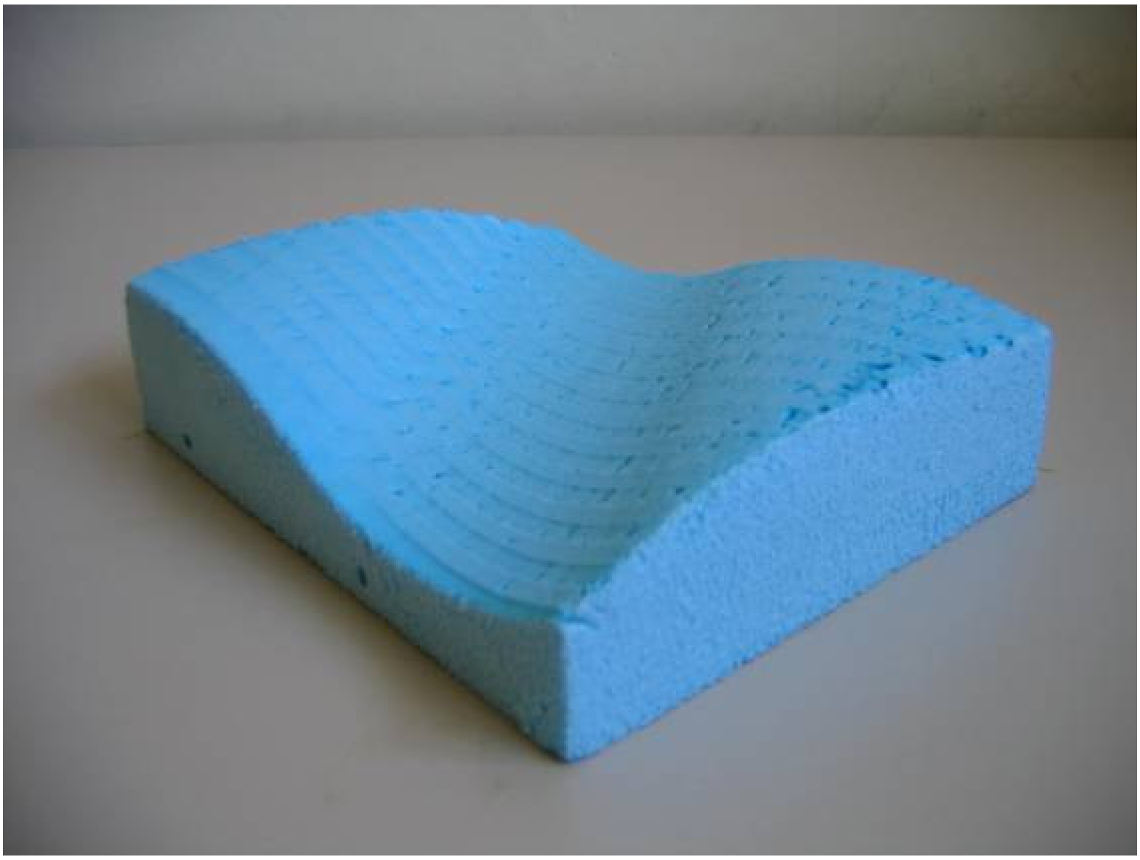


Figure 3.4-20 - Trial 7 overall photograph

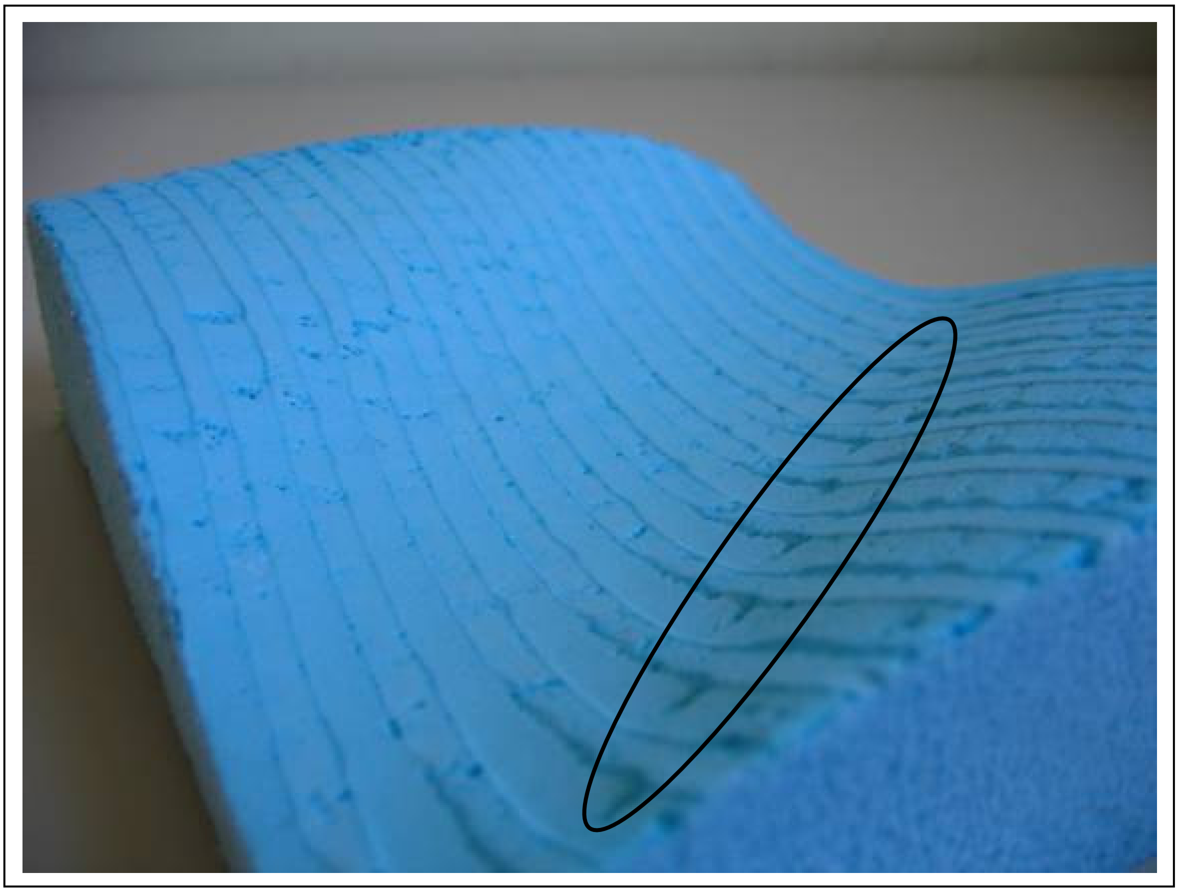


Figure 3.4-21 - Trial 7 close-up photograph

The following observations were made regarding the cut sample from trial 7:

- As can be seen from figures 3.4-20 and 3.4-21, the surface finish is remarkably more consistent than that of trial 6. This is primarily due to the fact that the robot's velocity was constant over the entire path due to the increased axis velocity limits.
- The sample exhibited fewer defects than previous trials but nevertheless still possessed them. The majority of the defects existed at the overlapping regions of adjacent passes.
- The alternating high/low surface profile created by the temperature variation was not as severe as that of previous trials as can be seen in figure 3.4-21. Like previous trials, the temperature variation is only really noticeable at each of the ends where an entry pass is juxtaposed with an exit pass. The reason that the temperature variation was not as severe as previous trials can be explained as follows: Due to the increased axis velocity limits, the tool could turn around quicker at the end of each pass, allowing it less time to heat up again. Subsequently, it entered the foam at a temperature which was closer to that of when it exited.
- By increasing the robots default maximum axis velocities, the robot could change orientation much quicker. This was especially noticeable in the time it took to turn around at the end of each pass. The changes resulted in a 30% reduction in machining time from 246 seconds to 175 seconds (includes roughing and finishing).
- As shown in figure 3.4-21, there are regions of individual passes that exhibit smooth defect free surfaces. These are generally located mid pass. This indicates that there exists an optimal tool velocity and temperature combination that can produce defect free accurate surfaces.

- An unusual defect appeared on this trial as indicated by the black ring in figure 3.4-21. The defects consist of deep melted pockets which align themselves on a diagonal line of inflection between the concave and convex regions of the surface. Possible explanations for this defect are: An instantaneous pause caused by the robot linkages changing direction, the interaction of the trailing edge of the blade with the foam, gouging due to the tool dimensions relative to the surface geometry or an instantaneous pause or slowing due to the tools tip being incorrectly measured. One would expect this defect to manifest itself on the other point of infection on the other side of the curve but it does not.

Trial 7 showed an improved surface finish due to the delimiting of the robot's axis velocities. It was apparent that the majority of the defects to date arose from the overlap between adjacent passes. This was mainly because a portion of the tool not engaged in the foam during the cut hovered over the previously cut surface re-melting it and causing defects. It was decided to investigate means of reducing such overlap effects through subsequent trials.

3.4.3.8 Trial 8

In order to improve the surface finish, it was decided that the re-melting effect at the overlap regions needed to be minimised. This trial involved pausing the robot at the beginning of each pass and wetting the already cut surface with a spray bottle, in an attempt to protect the already cut surface from re-melting when the edge of the hot blade passed over it. Apart from the water spray the conditions for the test were the same as for trial 6 and 7 and are shown below in table 3.4-8.

Table 3.4-8 - Trial 8 data

Attribute	Value
Tool velocity	0.075 ms^{-1}
Blade profile	
Blade size	8 mm
Path type	
Path spacing	6 mm
Rough cutting time taken	45 seconds
Finish cutting time taken	130 seconds
Total machine time	175 seconds

Figures 3.4-22 and 3.4-23 show an overall photo of the cut sample and a close-up shot respectively.

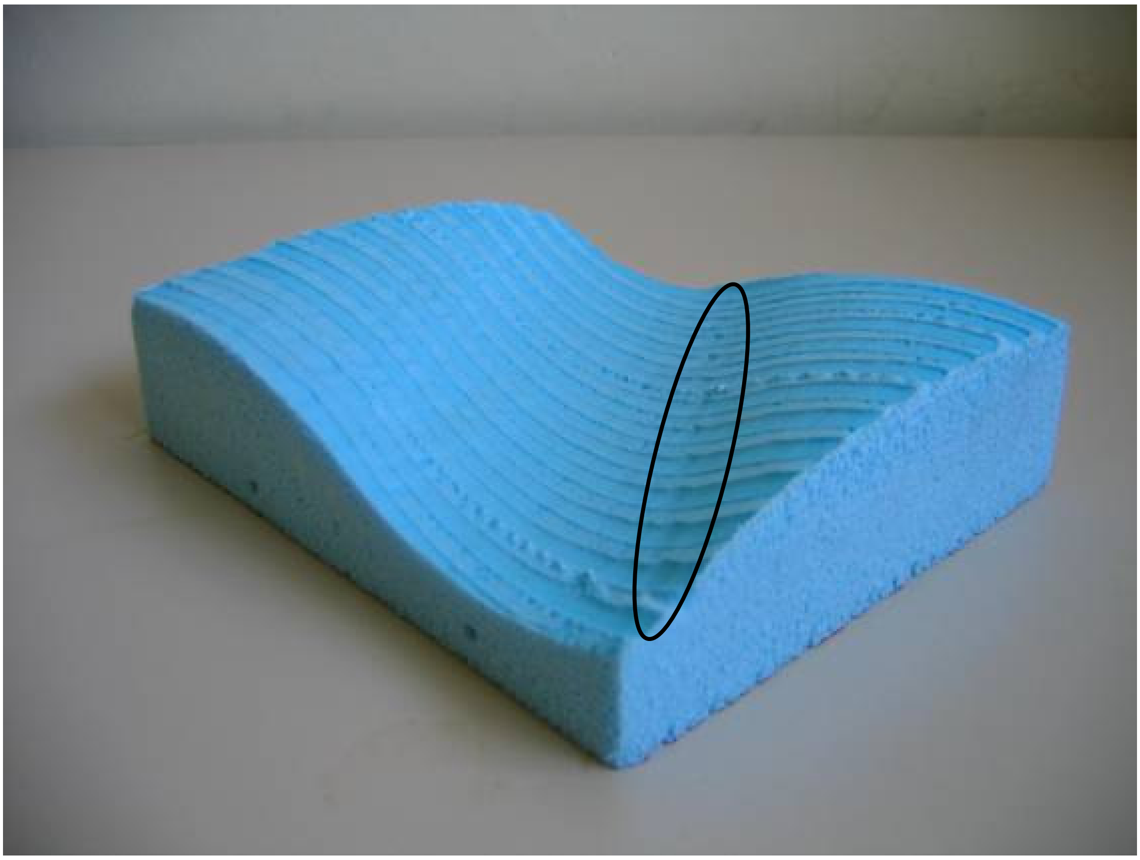


Figure 3.4-22 - Trial 8 overall photograph

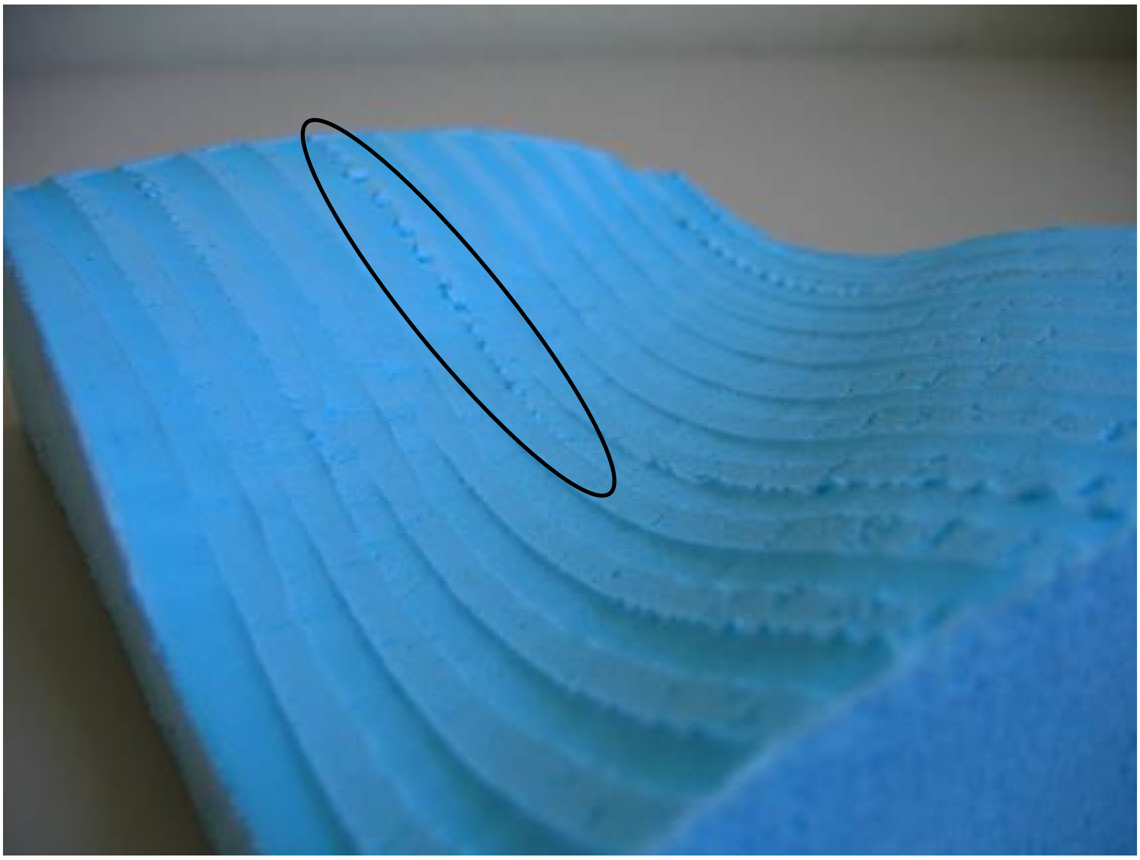


Figure 3.4-23 - Trial 8 close-up photograph

The following observations were made regarding the cut sample from trial 8:

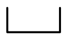
- The water spray on the already cut surface seemed to eliminate the unwanted overlap effects. As can be seen from figures 3.4-22 and 3.4-23, the surface finish is also noticeably free of the conventional spot-melt type defects.
- The surface finish indicates that the cutting was predominantly mechanical. This is especially evident in several portions of the surface where the foam was literally ripped by the cutting blade. One such area is shown encircled by the black ring in figure 3.4-23.
- The alternating high/low surface profile caused by blade temperature variation was very noticeable. The main reason for this is that, the tool was paused prior to each pass while the surface was sprayed, therefore allowing the blade's temperature to increase more than usual.
- The same peculiar lines of defects as in trial 7 were evident, as indicated by the black ring in figure 3.4-22.

The water spray seemed to cool the surface sufficiently to reduce unwanted re-melt defects at overlaps and also general spot-melt type defects. The reduction of the latter type suggests that a certain balance of thermal and mechanical cutting (via temperature and tool velocity control) can produce defect free surface finishes.

3.4.3.9 Trial 9

Trial 9 was essentially the same as trials 6 and 7 but was performed on a different material, namely, EPS. As mentioned earlier, EPS is not as dense as XPS and is created through an expansion method as opposed to an extrusion method. Subsequently the object could be sculpted at a tool velocity 30% faster than in trials 6 – 8. The aim of the trial was to see how the EPS material behaved compared to the XPS. Conditions were as shown in table 3.4-9 below.

Table 3.4-9 - Trial 9 data

Attribute	Value
*Tool velocity	0.1 ms^{-1}
Blade profile	
Blade size	8 mm
Path type	
Path spacing	6 mm
Rough cutting time taken	33 seconds
Finish cutting time taken	105 seconds
Total machine time	138 seconds

Figures 3.4-24 and 3.4-25 show an overall photo of the cut sample and a close-up shot respectively.

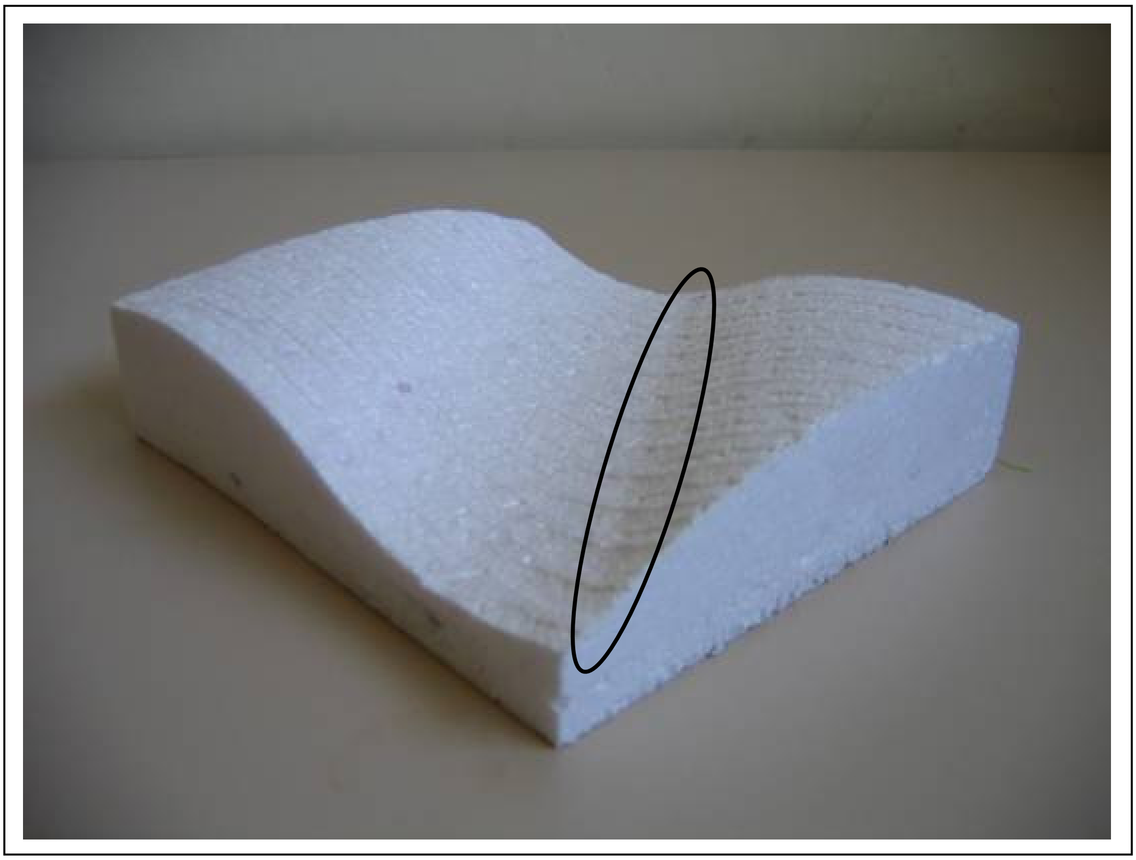


Figure 3.4-24 - Trial 9 overall photograph

Figure 3.4-25 - Trial 9 close-up photograph

The following observations were made regarding the cut sample from trial 9:

- The white colour of the EPS made the surface look better at first glance. However, after closer inspection, most of the defects common in the XPS foam were present. The same peculiar line of defects as in trials 7 and 8 were also evident but were not as pronounced. The line of defects is shown encircled by the black ring in figure 3.4-24.
- Close inspection of the local surface finish revealed that some of the EPS granules had been sheared while others had been completely ablated. In addition, air voids had also been exposed.
- The EPS foam requires a lot less heat input to cut. Subsequently cutting forces were low and the blade temperature variations seemed minimal. This is evident in the relatively small high/low alternating surface variation as can be seen in figures 3.4-24 and 3.4-25.
- The aforementioned low cutting forces enabled the sample to be sculpted faster than the XPS sample in trial 8. The total cutting time for trial 9 was a quick 138 seconds.

The first 9 trials all utilised bi-directional cutting paths which emphasised the often large variation in the blade temperature. Without some form of temperature control the efficacy of the process was hard to decipher. It was hence decided that subsequent trials should utilise uni-directional cutting paths which would annul the visible blade temperature variation effects.

3.4.3.10 Trial 10

Trial 10 utilised a uni-directional path to minimise the visible effects of blade temperature variation. The uni-directional path was produced by first creating a bi-directional path with a spacing of 3 mm (method as per section 3.4.2.2). Every second pass was then deleted resulting in a uni-directional path with a spacing of 6 mm. This was a rather tedious manual procedure which also involved inserting a robot command to effect the movement from the end of each pass back up to the beginning of the next. This monotonous procedure highlighted the need to use supplementary tool path generation and optimisation software. The XPS material was used again as it showed up the cutting defects more clearly. Conditions for the test were as shown in table 3.4-10 below.

Table 3.4-10 - Trial 10 data

Attribute	Value
*Tool velocity	0.075 ms^{-1}
Blade profile	└─┘
Blade size	8 mm
*Path type	│││││
Path spacing	6 mm
Rough cutting time taken	45 seconds
Finish cutting time taken	165 seconds
Total machine time	210 seconds

Figures 3.4-26 and 3.4-27 show an overall photo of the cut sample and a close-up shot respectively.

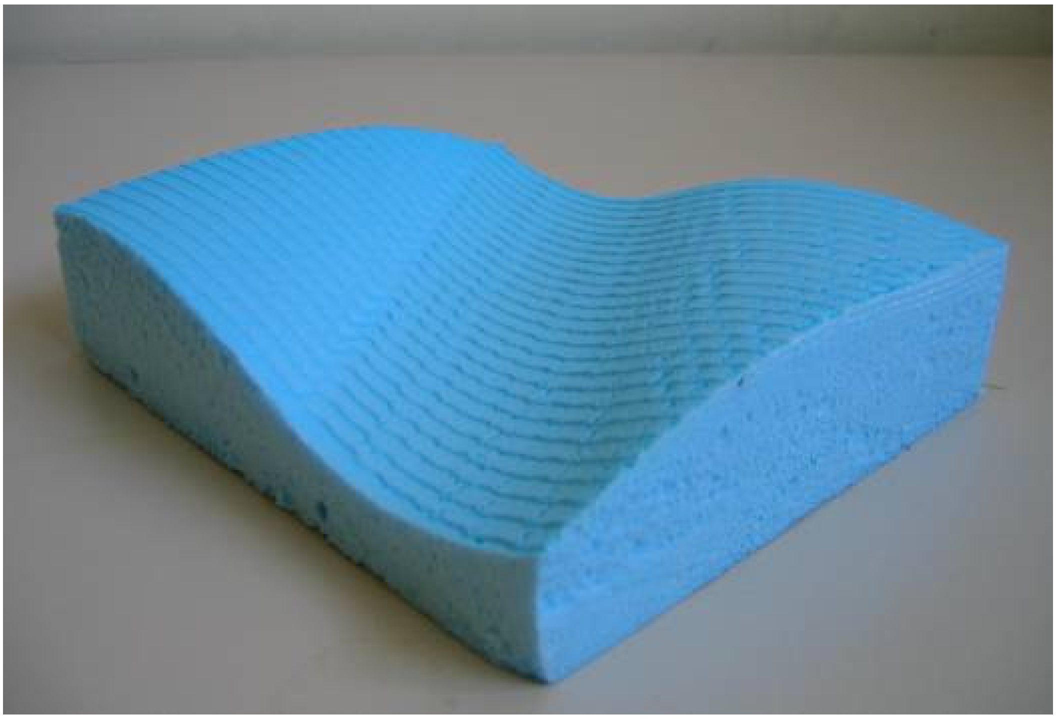


Figure 3.4-26 - Trial 10 overall photograph

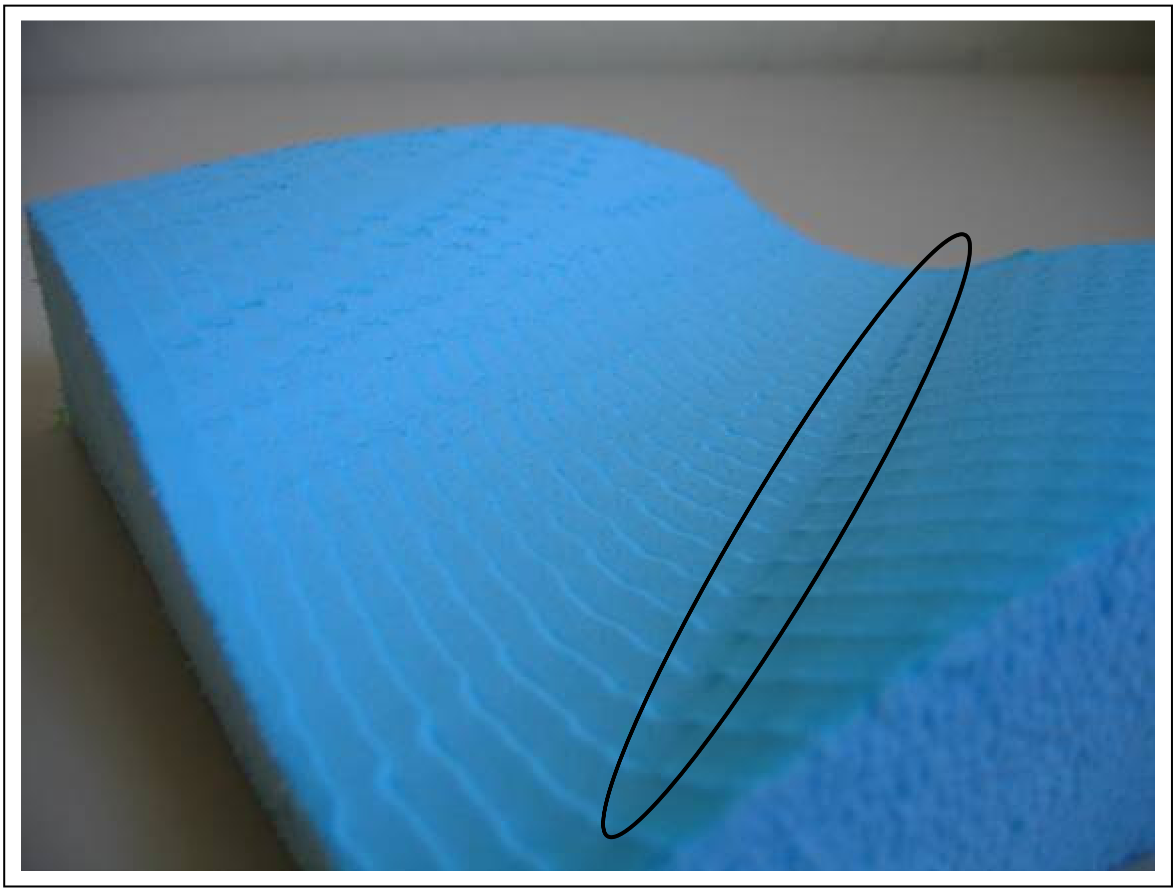


Figure 3.4-27 - Trial 10 close-up photograph

The following observations were made regarding the cut sample from trial 10:

- As can be seen from figures 3.4-26 and 3.4-27, the surface finish is substantially more uniform than the surface produced with a bi-directional tool path in trial 7. This was because each pass was in the same direction, meaning the blade temperature variation followed the same profile for each pass.
- The individual passes were remarkably defect free compared to previous trials. A large portion of defects were caused in previous trials by the depositing of molten material from the blade when it engaged with the foam upon entry and just after. In this trial the blade had sufficient time to vaporise any molten material on the blade before it re-entered the foam; due to the extended travelling time between each pass introduced by the uni-directional cutting path.
- The alternating high/low surface profile was absent; however, a new surface phenomenon presented itself. The visual and physical surface effect can be likened to that of a traditional weather-boarded house in the way that each pass possesses a low side and a high side, as illustrated by figure 3.4-26.
- The sample also exhibited the same diagonal line of defects as trials 7 – 9 although not as noticeable.

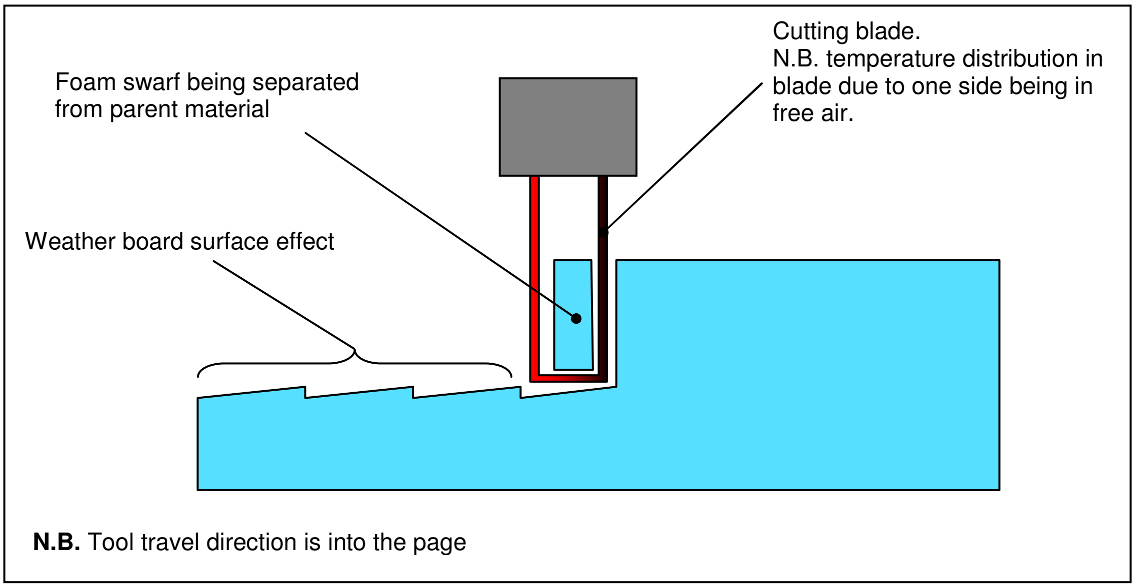


Figure 3.4-28 - Weather board surface effect

As shown by figure 3.4-28, the weather board surface effect is created by a combination of the blade sizing relative to the path spacing and the temperature distribution set up in the blade. In trial 10, an 8 mm blade was applied to a path with a spacing of 6 mm. Because the blade was wider than the path spacing, one side of the tool was engaged in the foam while the other side was just in free air. This imbalance established a temperature distribution in the blade which consequently created the weather board effect (i.e. hotter side of the tool removes more material than the colder side).

3.4.3.11 Trial 11

Trial 11 used some interesting geometry which consisted of a donut type shape. The geometry contained higher curvature than the previous geometry and of note, could not be manufactured with the common tight hotwire sculpting technologies, due to its central double concave feature. The focus of trial 11 was on the CAD model geometry and how the system handled it. EPS was used for the test since it produced lower cutting forces. The conditions for the trial were as outlined in table 3.4-11.

Table 3.4-11 - Trial 11 data

Attribute	Value
*Tool velocity	0.1 ms^{-1}
Blade profile	|___|
Blade size	8 mm
Path type	|||||
Path spacing	6 mm
Rough cutting time taken	30 seconds
Finish cutting time taken	125 seconds
Total machine time	155 seconds

Figures 3.4-29 and 3.4-30 show an overall photo of the cut sample and a close-up shot respectively.

Figure 3.4-29 - Trial 11 overall photograph

Figure 3.4-30 - Trial 11 close-up photograph

The following observations were made regarding the cut sample from trial 11:

- As can be seen in figures 3.4-29 and 3.4-30, the surface finish was relatively consistent and showed the same 'weatherboard' effect as in trial 10.
- The parts of the surface which had the worst surface finish were located in the high curvature double concave region. The defects in this region were primarily due to the tool being too large with respect to the local curvature, which resulted in gouging of the already cut surface by the corners of the tool.
- It was observed that during the cutting, especially through the double concave region, the blade supports and tool base came very close to colliding with the work in progress. Although collisions were checked for using RobotWorks, the observation, highlighted the fact that the complexity of the surfaces which can be sculpted may be limited by the tool design.

Due to the gouging problem in areas of high local curvature, it was decided to try reducing both the tool size and the path spacing.

3.4.3.12 Trial 12

It was initially decided that the CAD geometry used in test 11 be trialed with a smaller tool and path spacing in order to eliminate gouging, however, RobotWorks could not generate the desired path on the geometry for some peculiar reason. It was suspected that the dense tool path could not be projected onto the more complex surface due to insufficient computing power. The previous CAD geometry was hence used which caused no problems with RobotWorks. The conditions for trial 12 are shown in table 3.4-12 below.

Table 3.4-12 - Trial 12 data

Attribute	**Value**
Tool velocity	0.1 ms^{-1}
Blade profile	$\sqcup$
*Blade size	4 mm
Path type	$\vert\vert\vert\vert\vert$
*Path spacing	2.5 mm
Rough cutting time taken	35 seconds
Finish cutting time taken	320 seconds
Total machine time	355 seconds

Figures 3.4-31 and 3.4-32 show an overall photo of the cut sample and a close-up shot respectively.

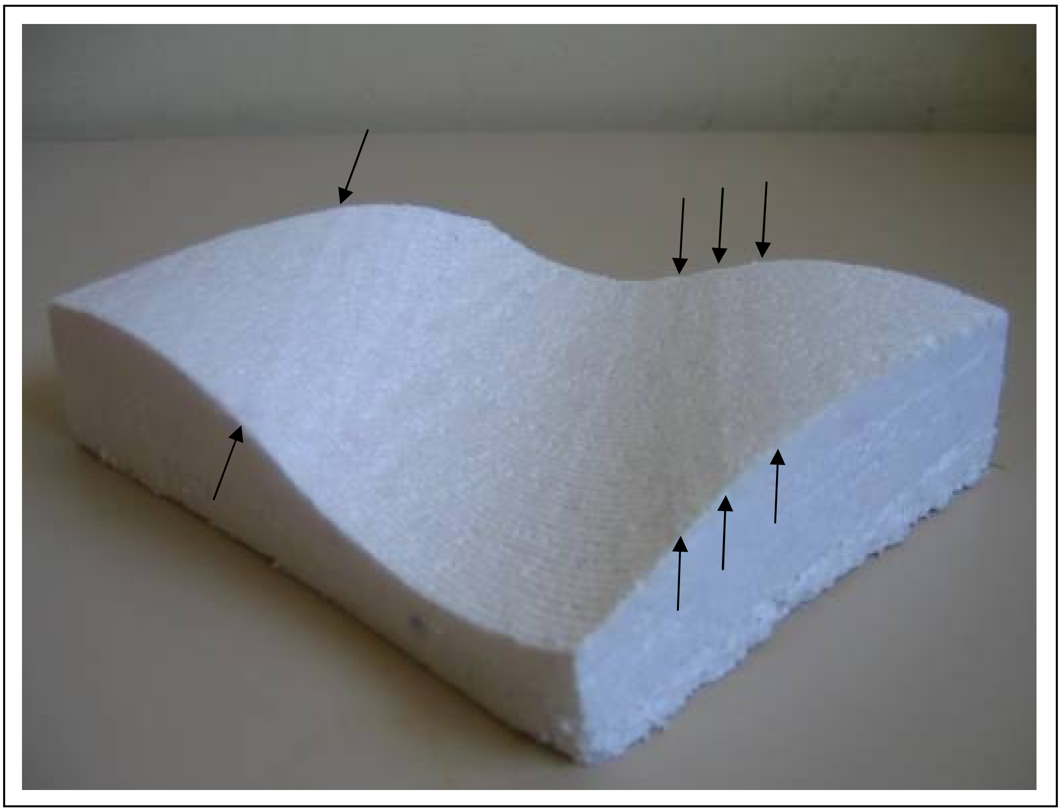


Figure 3.4-31 - Trial 10 overall photograph

Figure 3.4-32 - Trial 12 close-up photograph

The following observations were made regarding the cut sample from trial 12:

- Figures 3.4-31 and 3.4-32 show a much improved surface finish due to the smaller tool and path spacing. This was as expected, since the smaller tool is only capable of producing proportionally small defects.
- Due to a smaller path spacing the total machine time increased to 355 seconds compared to 210 seconds for trial 10 (path spacing of 6 mm and slower tool velocity of 0.075 ms^{-1}).
- The typical line of defects coinciding with the point of inflection was absent (as in trials 7 -10). However, another unique phenomenon came to light. The sculpted surface seemed to exhibit long facets which ran diagonally from edge to edge as indicated by the arrows in figure 3.4-31. This could possibly suggest that the number of points along the path was insufficient hence resulting in straight lines instead of curves as illustrated in figure 3.4-33 below. The density of the points can be altered in RobotWorks if necessary.

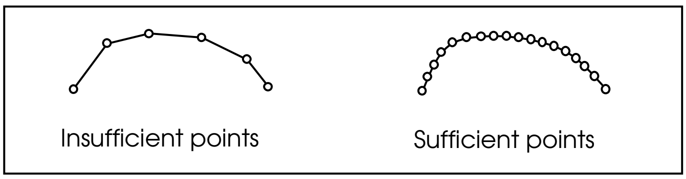


Figure 3.4-33 - Point density along a tool path

3.4.4 Preliminary 3D Sculpting Conclusions

The 12 conducted trials successfully proved that the system is capable of sculpting free form objects from polystyrene using a CAD model as the primary input. The surface finish and form achieved was improved over the duration of the testing as new information was harvested and applied. The following conclusions were made regarding the preliminary 3D sculpting trials.

- The concept of 3D sculpting using an articulated robot and electrically heated tool was proven. Furthermore, an object containing double concave surface regions was successfully sculpted, which cannot be achieved with conventional taut hotwire technologies.
- A large portion of the surface defects in the sculpted samples were caused by the overlap between successive passes. The heat output of the blade was sufficient to cause re-melt defects as it passed over all ready cut surfaces. The trials showed that a certain amount of overlap was needed to minimise the cusp between successive passes.
- The first six trials consistently showed that concave surfaces were more prone to defect than convex surfaces. It was postulated that the direction of the cutting force (away or into the foam) was a key factor in this.
- Melted holes were common at the beginnings of passes when bi-directional paths were used. These were caused by the deposit of molten material from the blade as it entered the foam. The defect did not arise when uni-directional paths were used since the molten material had more time to be vaporised from the blade before it re-entered the foam.
- It was found that if the tool was too large with respect to the local surface curvature it was sculpting, `gouging' occurred. This is where the TCP follows the tool path while the corners of the tool gouge into the surface which has already been cut.
- The trials showed that some form of active temperature control is needed to achieve good surface finishes. A high/low alternating surface profile was common on bi-directional paths due to the blade cooling significantly over the length of the pass. The uni-directional path was implemented to annul the visible effects caused by the temperature variation. This did work, however, the surfaces created would be inherently inaccurate (i.e. one end would be geometrically lower than the other end due to the cooling of the blade as it progressed from one end to the other).
- The best surface finish was achieved with the smallest tool (4 mm) applied to a path with the smallest spacing (2.5 mm between successive passes) as was expected. The main drawback in using such paths and tools is the significant machine time increase incurred.
- The process of generating tool paths using manually created projected sketches highlighted the need to automate the path generation step. The process was very time consuming and could not be applied to more complex geometry due to the difficulties involved with creating turn-around areas.

Overall, the preliminary 3D sculpting trials provided useful results which will be used to progress the research further. The next step is to investigate the means of automating the tool path generation step through use of common CAM software.

3.5 Advanced 3D Sculpting

3.5.1 Objectives

The preliminary 3D sculpting proved the concept of robotically effected sculpting of plastic foams using a CAD model as the process input. A crude procedure was developed which enabled the realisation of sculpted artefacts from their CAD models. This procedure was somewhat limited and overtly manual. The main objective of the advanced 3D sculpting experimental work was to develop the procedure to make it more automated. Of particular importance was the automation of the critical tool path generation and optimisation step.

In addition to automating the tool path generation and optimisation step, it was intended that the newly developed procedure be put to use on a practical application. The practical application was a patient customised medical radiation therapy head and neck support. The objectives can be summarised as below:

- Develop a procedure which has a higher level of automation.
- Assess the efficacy of the developed procedure by sculpting an arbitrary artefact created from scratch within a CAD system.
- Asses the efficacy of the developed procedure through the sculpting of a patient customised medical radiation therapy head and neck support.

3.5.2 Procedure

The design and development of the following procedure comprises a significant section of the authors work. The procedure outlines the steps taken to sculpt freeform surfaces in a semi-automated fashion using a CAD model of the object as the primary input to the process. Of particular note is the automation of the tool path generation and optimisation process. The experimental procedure comprises the following five steps:

1. Generation of the CAD model to be sculpted
2. Tool path generation and optimisation
3. Post processing of the generated tool path
4. Simulation and robot control program creation
5. Setup and implementation

Figure 3.5-1 contains a flow chart to summarise the newly developed procedure. Each of the five steps is then explained in detail following the flow chart.

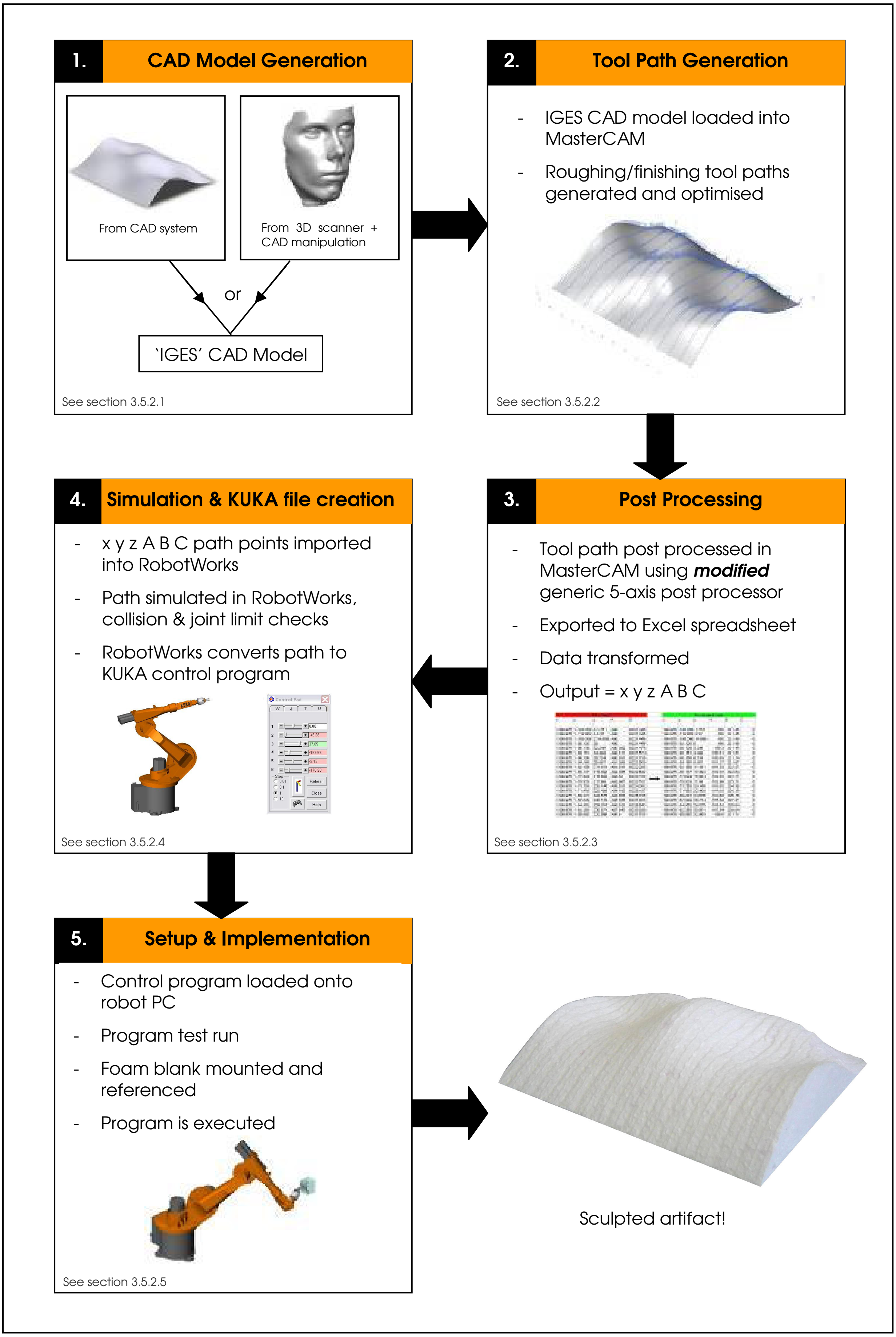


Figure 3.5-1 - Procedure summary

3.5.2.1 CAD Model Generation

Unlike the preliminary sculpting work, the CAD models are not required to be created in SolidWorks 2003 Educational Edition exclusively. This is because the newly developed procedure does not use SolidWorks to manually create tool paths from 3D curves for RobotWorks to operate on. Subsequently, the input CAD models can be produced using any method, provided they can be converted to the IGES file format. The IGES file format is a neutral format which allows the model to be transferred between a large number of CAD and CAM packages. Of particular note is the compatibility with MasterCAM, a tool path generation and optimisation package which can produce 5-axis tool paths on CAD models represented in the IGES format (see section 3.5.2.2).

Two distinct methods of creating CAD models for the input to the foam sculpting system were implemented. The first involved creating a simple lofted surface in SolidWorks. The second method was more complex and involved utilising point cloud data generated from a 3D scanner.

Figure 3.5-2 shows the creation of a simple lofted surface produced in SolidWorks.

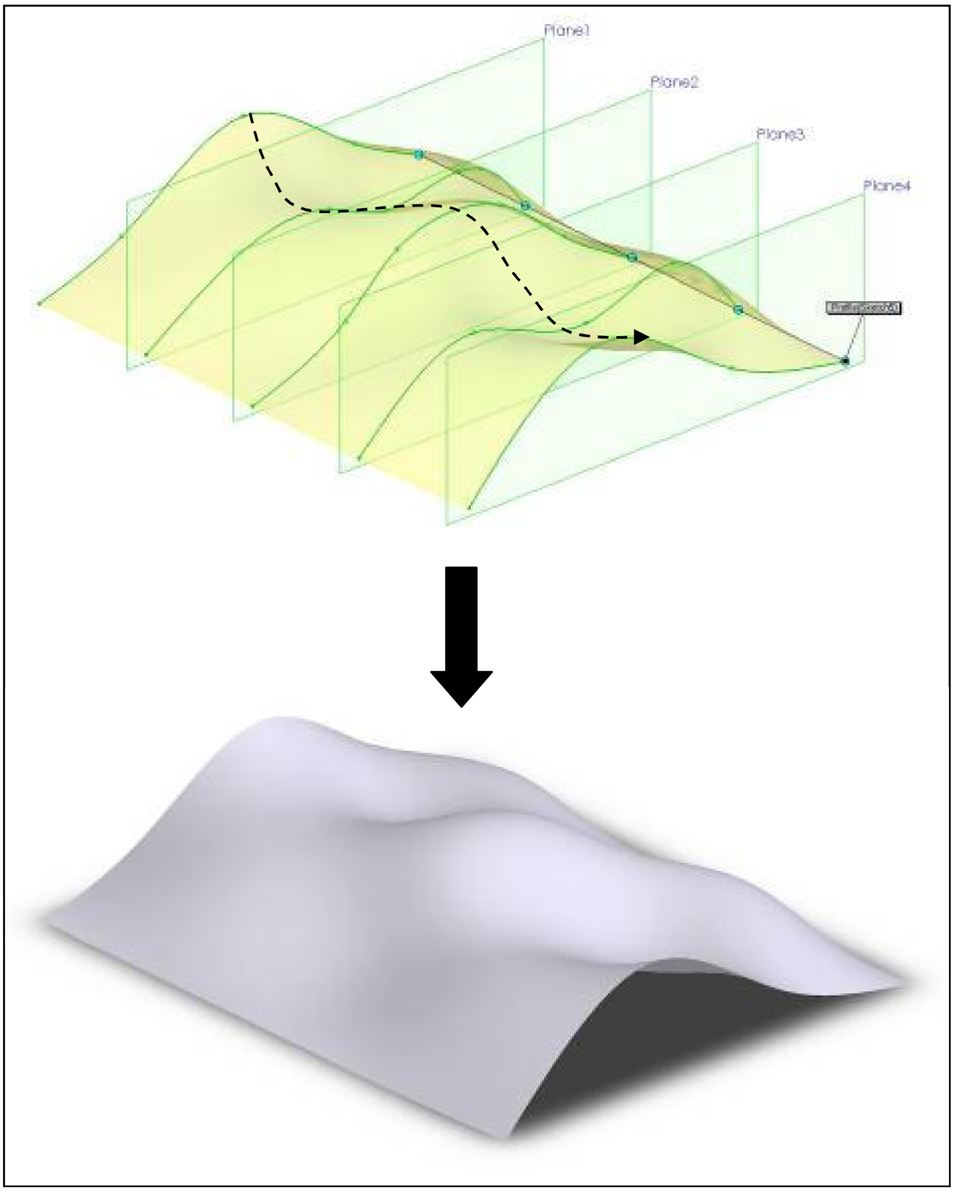


Figure 3.5-2 – Lofted surface created in SolidWorks

As can be seen in figure 3.5-2, the lofted surface incorporates five distinct cross-sections which were lofted over. Each cross section was drawn on its own plane by using a spline creation tool. It should be noted that the CAD model did not need to be a surface but could have been a solid also. The lofted surface is then exported in the required IGES format as a single smooth continuous surface. Creating the model from scratch within a CAD system is ideal, provided the model can be confidently created as per the geometrical requirements. This method works well until customised free-form or 'organic' surfaces are required. At this point it is extremely helpful to use auxiliary technology such as 3D scanners to aid the generation of the CAD model.

As previously mentioned, the second method involved the utilisation of point cloud data acquired from a 3D scanner. A 'Polhemus FastScan' 3D scanner was used in the development of this work to obtain point cloud data from physical models. Figure 3.5-3 shows the FastScan 3D scanner which is a hand held laser based device that relies on electromagnetic fields for its spatial and orientational positioning system.

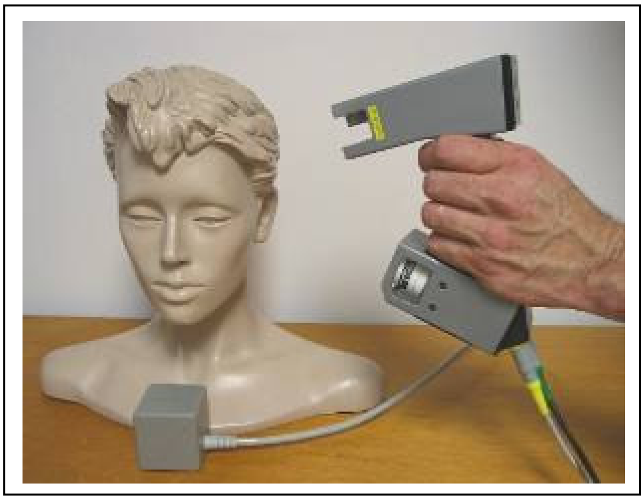


Figure 3.5-3 - Polhemus FastScan hand-held laser based 3D scanner

The raw scanned point cloud data of a human forearm (elbow to wrist) accompanied with its processed and re-meshed counterpart is shown in figure 3.5-4.

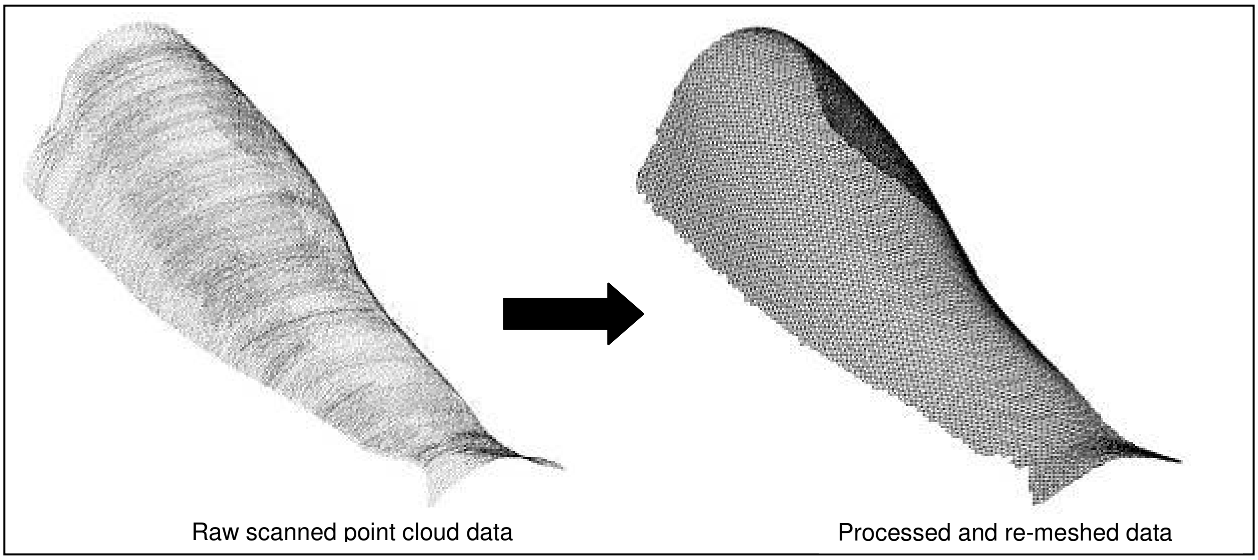


Figure 3.5-4 - Scan data of a forearm

Using the 3D scanner is much like spray painting in the fact that several sweeps over the physical model are required to obtain the complete surface. The first image in figure 3.5-4 shows the raw point cloud data obtained from the 3D scanner. Each data point is randomly spaced and could also coincide with identical points from multiple sweeps. The data is subsequently not suitable to create a CAD model from directly. FastScan software is used to process the data and generate uniformly spaced point cloud data. The software uses a radial basis function algorithm to mathematically fit a re-meshed uniform surface. This processed model is then exported as an ASCII .TXT file. Additionally, the processed model can be exported as a .STL file (see section 2.2.1 for explanation on .STL files), however, the majority of CAM packages cannot perform 5-axis tool path generation and optimisation on them (most can perform 3-axis though). The .TXT file contains three columns. Each row contains the x, y and z coordinates of a single data point. It should be noted that the .TXT file is essentially the same as the .STL file except it is missing the information pertaining to the surface normal of each triangular facet. The points in the .TXT file are merely the vertices of the triangular facets.

Conversion of the point cloud data (in the form of a .TXT file) to an IGES file can be achieved using auxiliary software such as Geomagic Studio (27). This package essentially fits a collection of knitted discreet surface patches to the point cloud data. Figure 3.5-5 shows the surface patching of an object in Geomagic Studio. It should be noted that the point cloud data has been rendered to appear as a surface.

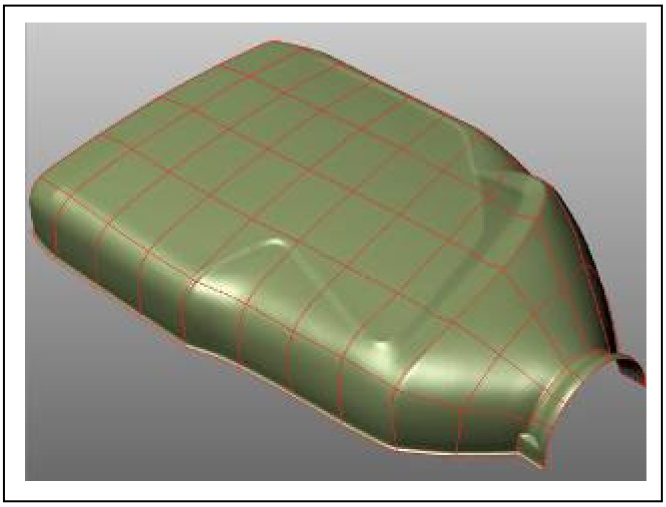


Figure 3.5-5 - IGES surface patching of point cloud data in Geomagic Studio (27)

The Department of Mechanical Engineering does not have a licence for any such surfacing software, hence necessitating a 'work around'. The 'work around' involves the following two steps:

1. Slices of the point cloud data are taken to obtain cross section profiles at intervals along the length of the model.
2. The cross section profiles are used to loft a surface over in SolidWorks, therefore recreating the object with a single surface.

The first step is achieved through the implementation of a Matlab program which was specially designed. The program essentially generates cross sections of the object at user specified intervals. Each cross section is saved as a .SLDCRV file (SolidWorks curve file) which is simply a text file with three columns where each row contains the x, y and z coordinate of a single point on the cross section. The Matlab program is provided in Appendix B.

Step two involves opening the .SLDCRV files in SolidWorks. Figure 3.5-6 shows a .SLDCRV file along with its graphical representation when opened in SolidWorks.

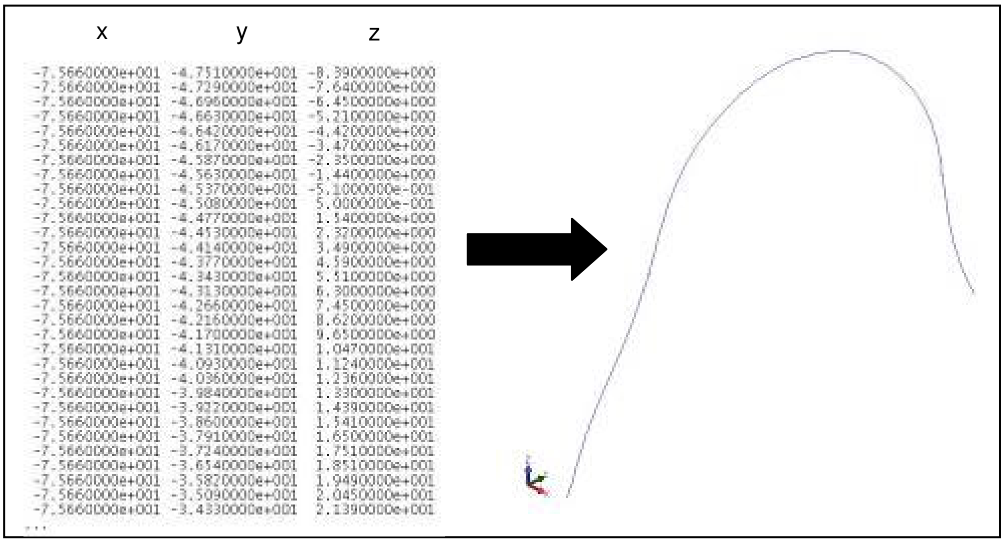


Figure 3.5-6 - Importing cross section files into SolidWorks

In order to recreate the surface, all of the generated cross sections are opened in SolidWorks where a lofted surface is produced over them. Figure 3.5-7 shows 14 cross sections and the lofted surface created with them. The cross sections were taken at 20 mm increments down the length of the arm which was scanned with the FastScan 3D scanner.

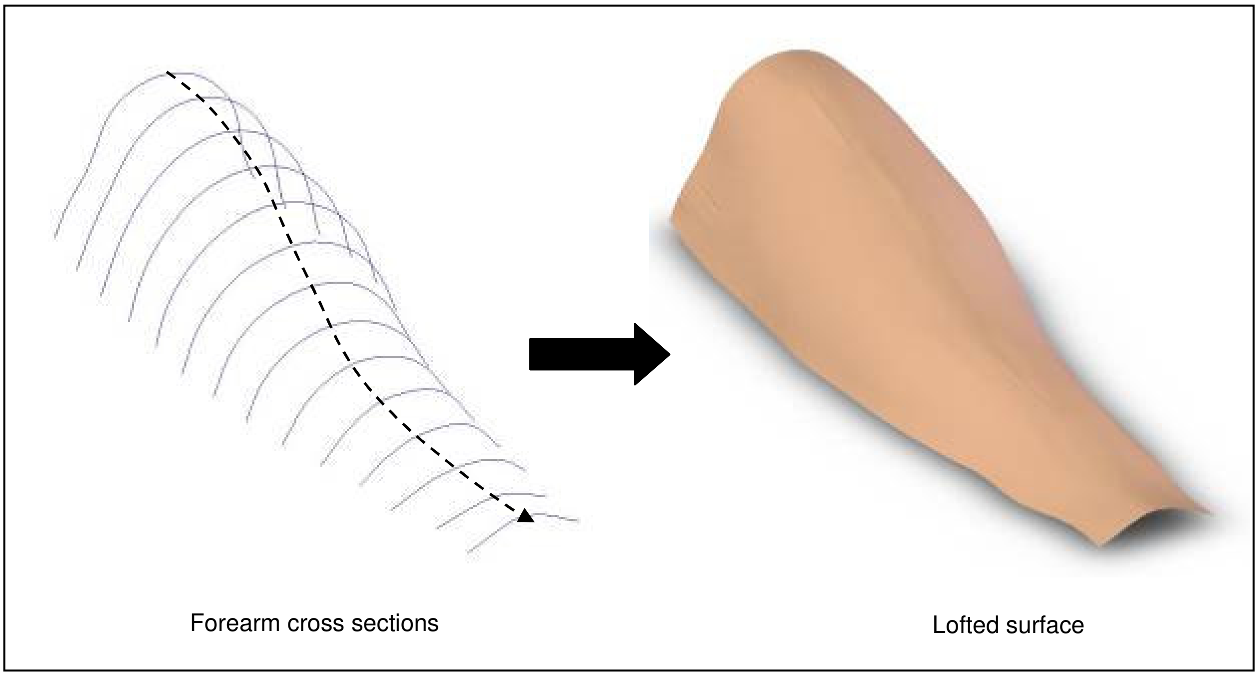


Figure 3.5-7 - Lofting between imported cross section curves in SolidWorks

The lofted surface is then exported in the required IGES format as a single smooth continuous surface. If the object to be sculpted was more complex, more cross sections would be needed to re-create the surface of the object to an accurate level.

3.5.2.2 Tool Path Generation with MasterCAM

In the preliminary 3D sculpting work, tool paths were manually generated by projecting a sketch of the tool path onto the 3D surface. The parameters such as spacing between successive passes and path direction were controlled by manually altering the sketch. In addition, if the tool was intended to over run the model at either end, the CAD model had to be extended in order to project the path sketch on to it. The procedure was somewhat limited and small modifications to the path (such as path spacing and direction) required extensive rework.

The newly developed procedure utilises a CAM software package called MasterCAM (see Appendix A.2 for MasterCAM brochure). MasterCAM is one of the leading CAM packages available and is an extremely powerful tool for generating and optimising tool paths. MasterCAM has not been designed for use with 6-axis articulated robots but rather with CNC mills, routers, lathes and EDM wire cutters. This posed a problem in terms of the paths that were generated and the format in which they were outputted. In order to effectively sculpt surfaces with the Robot and heated tool configuration, a path was required which could maintain the tool normal to the surface at all times. If this could not be achieved, the tool would easily get bent during operation. The 5-axis advanced tool path generation and optimisation module was used in MasterCAM to create tool paths on the models to be sculpted. The following steps can be followed to generate optimised tool paths:

1. The CAD model in its IGES format is opened within the MasterCAM environment.
2. A '5-axis table horizontal' machine definition is chosen for the machine type. This type is chosen since it is the closest to an articulated robot in terms of its spatial and rotational co-ordinate system.
3. The advanced 5-axis tool path module is opened. A tool is then chosen (the tool selection is arbitrary since the output is independent of the tool length, type or size but nevertheless needs to be chosen to complete the process).
4. The next step is to select the surface to be operated on. This is done by a single click on the continuous IGES surface. A user form is then employed to control the generation of the tool path on the chosen surface. This user form is shown in figure 3.5-9 and will now be explained according to each of the form's inputs/options.
    a. The first group of options under the title 'Pattern' are used to control the particular path pattern and direction. The most common pattern used is the 'parallel cuts' pattern which simply creates passes which are all parallel. The angle at which the parallel path is made can be altered in both the xy and zx planes. Additionally, an offset from the surface can be applied.
    b. The second group of options under the title 'Area' are used to control the portions of the generated path at the edges of the defined area. The 'Type' option can control whether or not the starting and ending passes are coincident with the surfaces edges. The 'extend/trim' function controls the amount that the path is extended or trimmed with regard to the surface edges at the end of each pass. As shown by the second user form in figure 3.5-9, either a specific value can be set in mm, or the value can be set as a certain percentage of the tool diameter. The 'extend/trim' function is analogous to the tool turn around area required in the preliminary 3D sculpting work.

c. The group of options entitled 'Sorting' controls the cutting method and order. The 'cutting method' allows the user to choose between a uni-directional path and a bi-directional path (zig-zag). If a uni-directional path is chosen, the movements between the end of one pass and the beginning of the next are automatically programmed. The 'cut order' allows the user to specify the order in which material is removed. The options are; 'standard' – material is removed sequentially from one end to the other, 'centre away' – material is removed symmetrically from the centre out, and 'outside to centre' – material is removed symmetrically from the outside in. Figure 3.5-8 graphically shows the three cut order options. The check box labelled 'flip step over' allows the user to change the direction in which the path progresses in (i.e. from the left end to the right end or vice versa). An additional option is the 'start point', which permits the user to manually specify a particular start point for the path.

d. The final set of options labelled 'surface quality' allow complete control over the accuracy of the machined surface (within limits of the robot of course). The 'cut tolerance' specifies the maximum variation between the generated tool path and the actual CAD model surface. The 'distance' can control the path point discretisation along the length of the passes. This value is set in mm and is the maximum point spacing that will be applied. Another control, not on this form, is the 'maximum angle step'. This also specifies the path point discretisation along the length of the pass, but in terms of the angle difference between successive points. The final discretisation is governed by the dominant control (distance or angle). The 'maximum stepover' allows the user to specify the spacing between passes in mm. The value can be varied depending on whether the pass is a roughing pass or a finishing pass. For example, the value could be set at 20 mm for a roughing pass and 3 mm for a finishing pass. It should be noted that the step over is typically chosen according to the tool size.

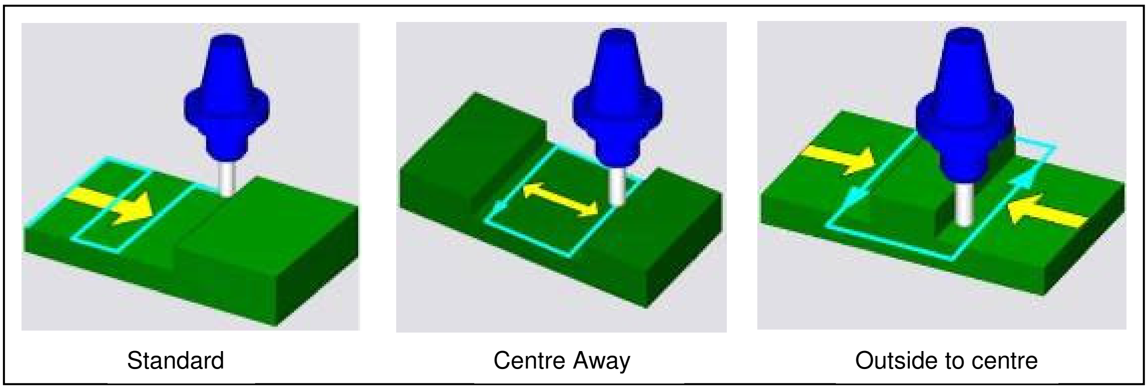


Figure 3.5-8 - Cut order options in MasterCAM

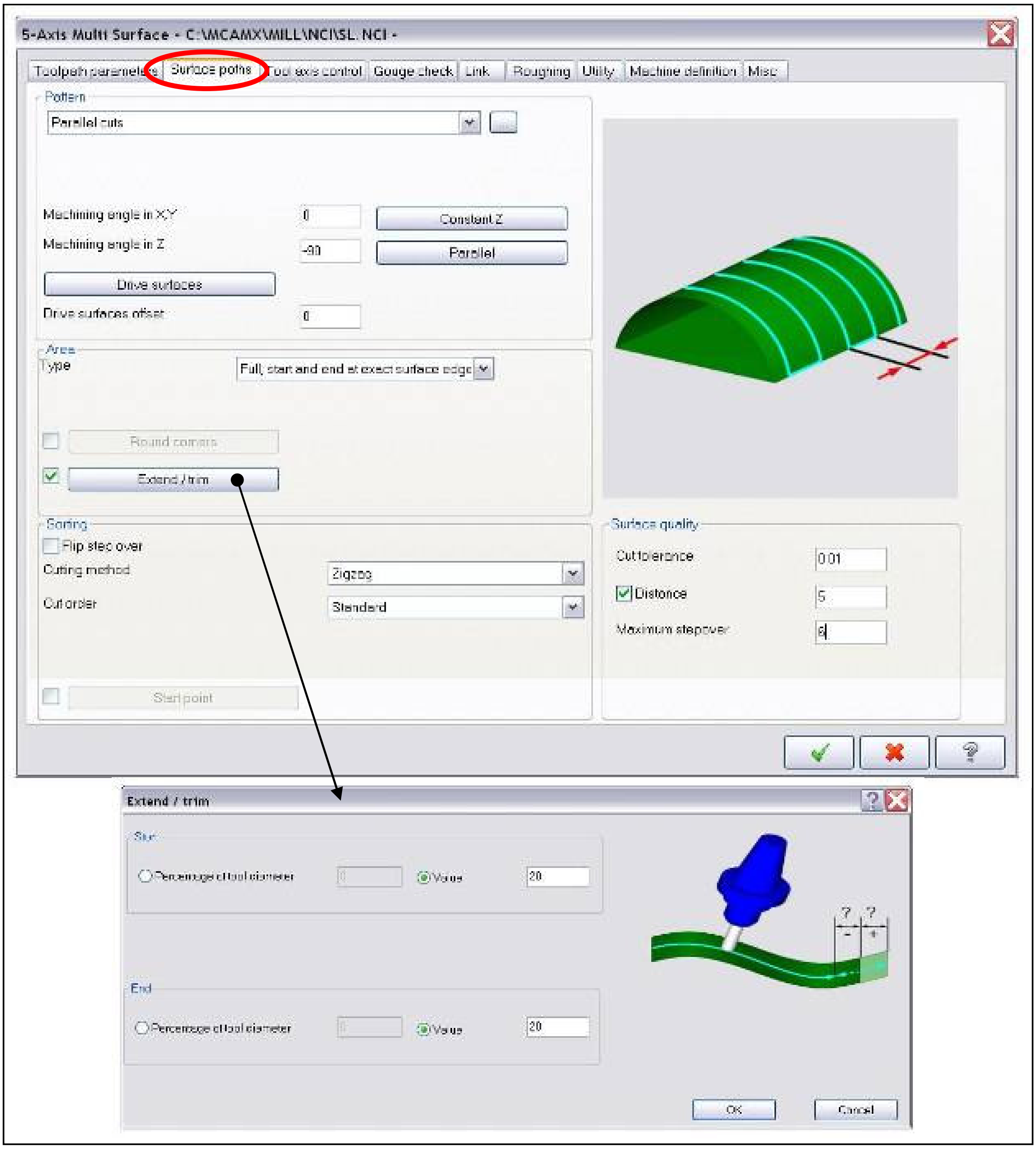


Figure 3.5-9 - Tool path parameters in MasterCAM

5. Once the pattern, edge options, extend/trim, cutting method, cut order and surface quality have all been defined, the tool axis control options can be specified. Another user form was utilised to control this and is shown in figure 3.5-10. The 'output format' option allows the user to specify whether the path uses 4-axis control or 5-axis control. As previously mentioned the 'maximum angle step' controls the path point discretisation along the length of the pass in terms of the angle difference between successive points. This value is set in degrees and essentially controls the sensitivity of the tool path to surface detail. For example, a larger maximum angle step would result in less path points in regions of higher surface complexity than if a smaller maximum angle step was used. The 'tool axis will…' option controls the behaviour of the tool with respect to the surface. In

order to maintain the tool normal to the surface at all times the option is set to 'not be tilted and stays normal to surface'. The other options included 'be tilted relative to cutting direction', 'tilted with fixed angle to axis' and 'tilted around axis'. The 'not be tilted and stays normal to surface' option was chosen since it would produce the best surface with the tool and robot configuration. The final user input for the user form is the 'run tool…' option. This specifies the point on the tool which contacts the work piece. The options are; 'Auto' – tool contact point changes to suit conditions, 'at centre' – tool contact point is at the geometrical centre of the end of the tool, 'at radius' – the user can specify a radius from the centre of the end of the tool, 'at front' – tool contact point is always at the front with respect to the direction of travel and 'at user given point' – the user can specify any point to be in contact with the surface.

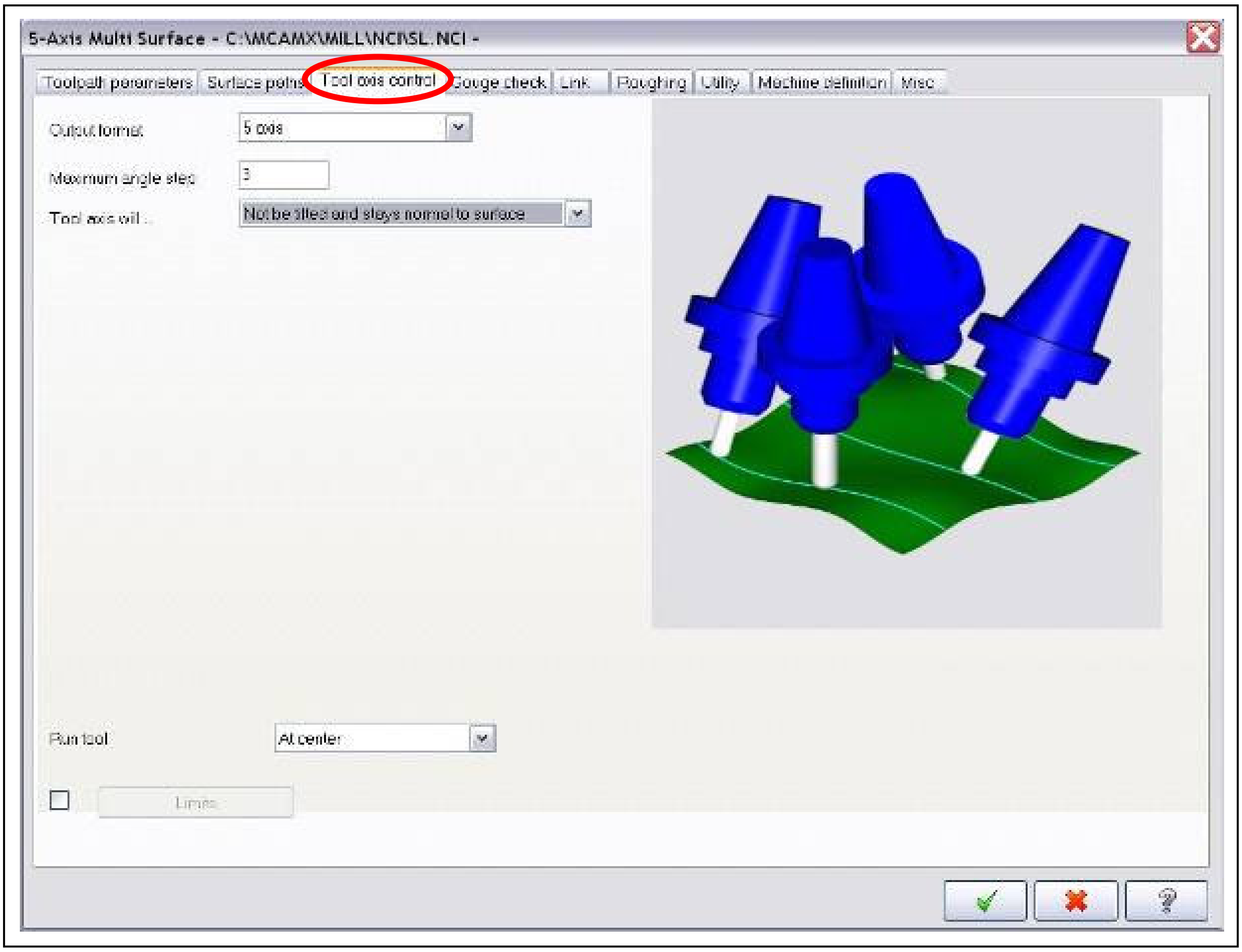


Figure 3.5-10 - Tool path parameters in MasterCAM continued

6. The final step simply involves checking the inputs and clicking the green tick shown in figures 3.5-9 or 3.5-10. The MasterCAM path generation algorithms then get to work generating the desired path on the surface. The process usually is completed in less than one minute.

Once calculated and generated, the tool path appears as a collection of vectors on the surface as shown in figure 3.5-11. Each vector delineates the position and direction for a single point on the tool path. As can be seen in figure 3.5-11, all of the path points are normal to the discreet portion of surface they represent.

If the path is not as desired, the advanced 5-axis user forms can be opened and edited and the tool path can be regenerated within a few seconds.

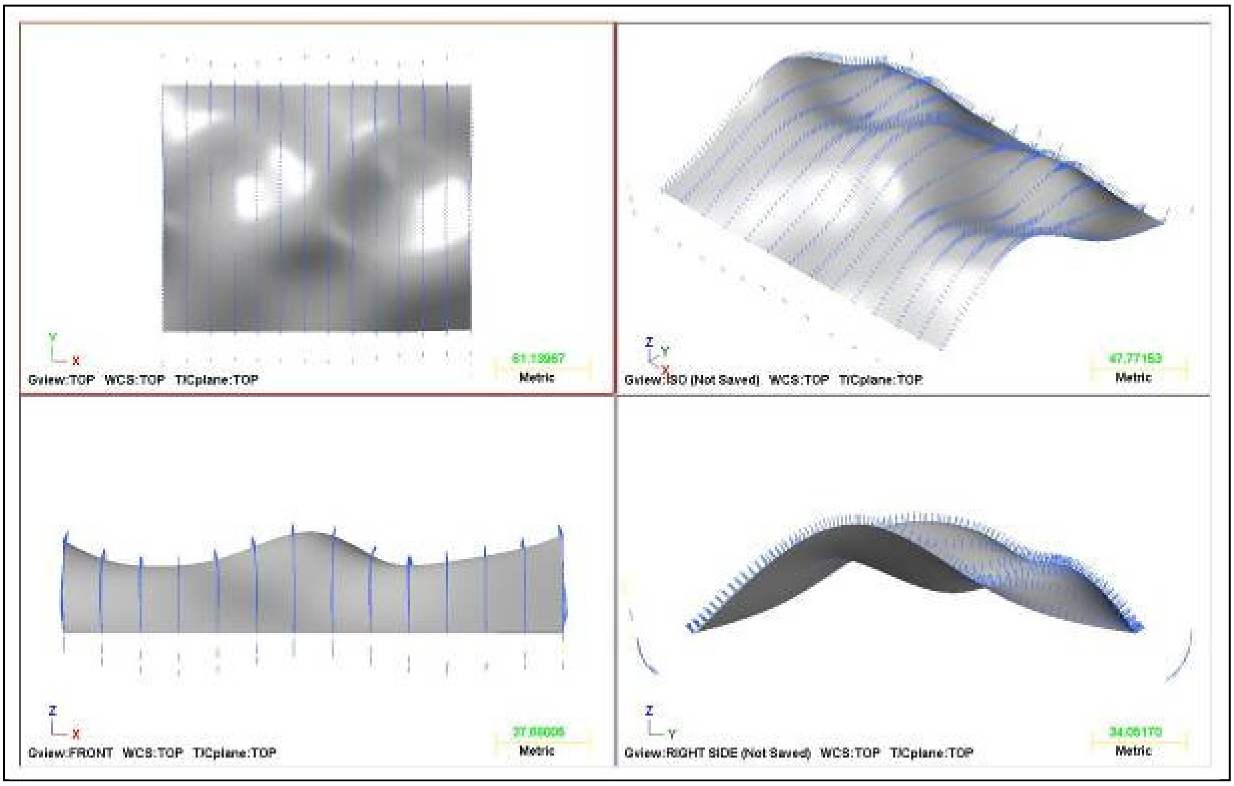
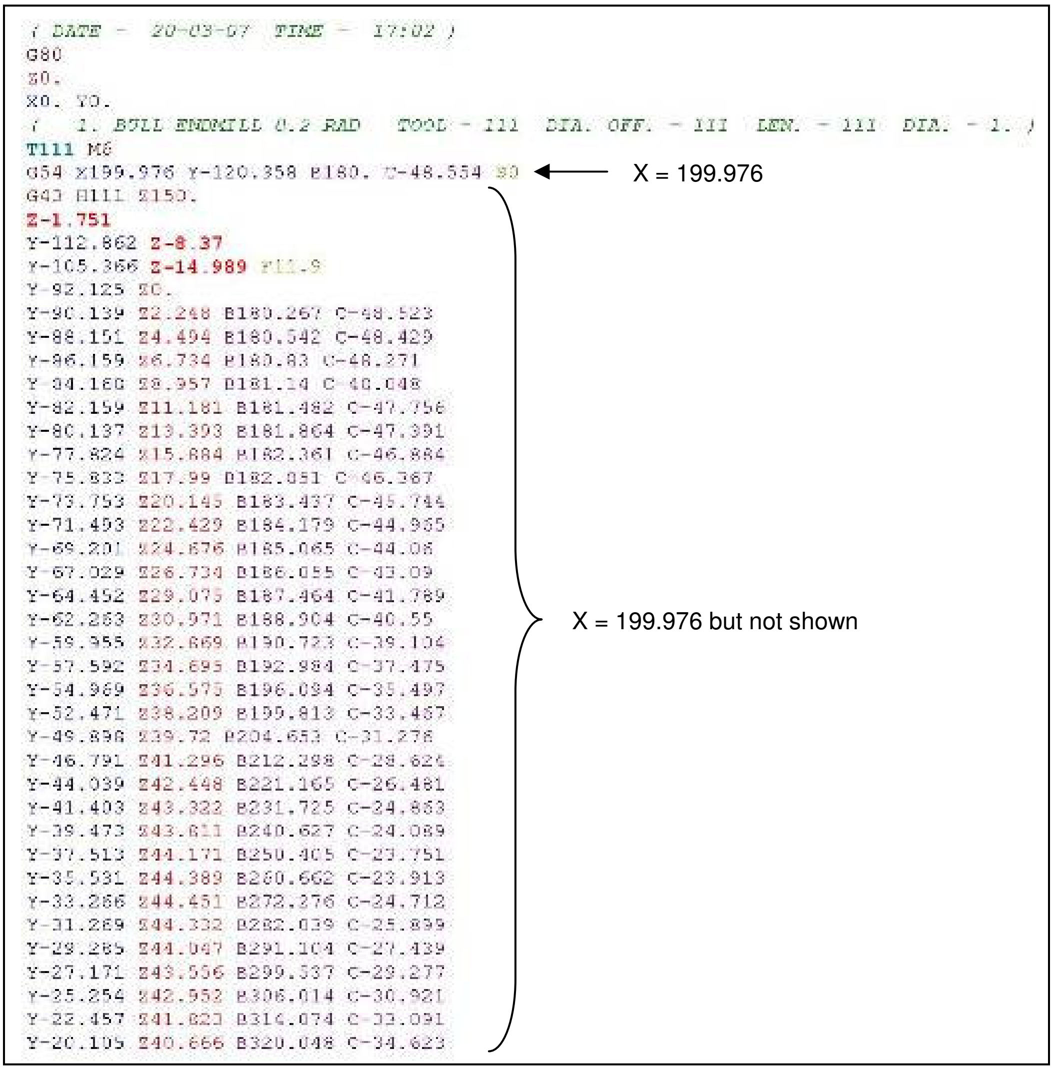


Figure 3.5-11 - Tool path generated on a surface in MasterCAM

3.5.2.3 Post Processing

Once the desired path has been created, it needs to be 'post processed'. This in essence converts the path points with their spatial and orientational data to a format which can be read by a CNC machine. Because MasterCAM does not support 6-axis articulated robots, the output had to be modified to be of any use. Two main problems were evident with the post processed data from the generic 5-axis post processor. The first was the fact that the post processor did not output the data in the required x y z A B format but rather in the x y z B C format, where 'B' is the table tilt about the 'y' axis and 'C' is the table rotation about the 'z' axis (spindle direction on machine).

The second problem was with regard to the 'modal' entry of coordinates. The coordinates were only entered in the line if their value was different than in the previous line. For example if a parallel pass was created with each pass having constant 'x' coordinates, the 'x' coordinate would only be written once at the beginning of the pass. This was inconvenient since RobotWorks required six coordinates for every single point along the path (x y z A B C). Figure 3.5-12 shows the output from the generic 5-axis post processor.



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Z0.
X0. Y0.
(   1. BULL ENDMILL 0.2 RAD   TOOL - 111  DIA. OFF. - 111  LEN. - 111  DIA. - 1. )
T111 M6
G54 X199.976 Y-120.358 B180. C-48.554 S0
G43 H111 Z150.
Z-1.751
Y-112.862 Z-8.37
Y-105.366 Z-14.989 F11.9
Y-92.125 Z0.
Y-90.139 Z2.248 B180.267 C-48.523
Y-88.151 Z4.494 B180.542 C-48.429
Y-86.159 Z6.734 B180.83 C-48.271
Y-84.160 Z8.957 B181.14 C-48.048
Y-82.159 Z11.181 B181.482 C-47.756
Y-80.137 Z13.393 B181.864 C-47.391
Y-77.824 Z15.884 B182.361 C-46.884
Y-75.833 Z17.99 B182.851 C-46.367
Y-73.753 Z20.145 B183.437 C-45.744
Y-71.493 Z22.429 B184.179 C-44.965
Y-69.201 Z24.676 B185.065 C-44.06
Y-67.029 Z26.734 B186.055 C-43.09
Y-64.452 Z29.075 B187.464 C-41.789
Y-62.263 Z30.971 B188.904 C-40.55
Y-59.955 Z32.869 B190.723 C-39.104
Y-57.592 Z34.695 B192.984 C-37.475
Y-54.969 Z36.575 B196.034 C-35.497
Y-52.471 Z38.209 B199.813 C-33.487
Y-49.898 Z39.72 B204.653 C-31.278
Y-46.791 Z41.296 B212.298 C-28.626
Y-44.039 Z42.448 B221.165 C-26.481
Y-41.403 Z43.322 B231.725 C-24.863
Y-39.473 Z43.811 B240.627 C-24.089
Y-37.513 Z44.171 B250.405 C-23.751
Y-35.531 Z44.389 B260.662 C-23.913
Y-33.266 Z44.451 B272.276 C-24.712
Y-31.269 Z44.332 B282.039 C-25.899
Y-29.265 Z44.047 B291.104 C-27.439
Y-27.171 Z43.556 B299.337 C-29.277
Y-25.254 Z42.952 B306.014 C-30.921
Y-22.457 Z41.823 B314.074 C-33.091
Y-20.105 Z40.666 B320.048 C-34.623
```


Figure 3.5-12 - Output from MasterCAM with original generic 5-axis post processor

To solve the problem, the generic 5-axis post processor was modified by carefully editing the program's code in order to obtain the desired output. The first modification was to suppress the 'C' coordinate output and allow the 'A' coordinate to be outputted. In addition, the calculation of the values for the rotational coordinates 'A' and 'B' were modified to output absolute values less than 360º. The post processor usually outputs the rotational coordinates in a manner which allows them to keep counting past 360º.

The second modification was to force all five coordinates to be written for every single point along the path. The data was now complete for each point and could be used with RobotWorks. Figure 3.5-13 shows the output from the modified post processor. It should be noted that the output shown in figure 3.5-12 and 3.5-13 is from the same tool path.

```
( DATE -  20-03-07  TIME -  17:04 )
G90
Z0.
X0. Y0.
(   1. BULL ENDMILL 0.2 RAD   TOOL - 111  DIA. OFF. - 111  LEN. - 111  DIA. - 1. )
T111 M6
G54 X199.976 Y-120.358 A90. B221.446 S0
G43 H111 Z150.
X199.976 Y-120.358 Z-1.751 A90. B221.446
X199.976 Y-112.862 Z-8.37 A90. B221.446
X199.976 Y-105.366 Z-14.989 A90. B221.446 F11.9
X199.976 Y-92.125 Z0. A90. B221.446
X199.976 Y-90.139 Z2.248 A90.302 B221.478
X199.976 Y-88.151 Z4.494 A90.611 B221.574
X199.976 Y-86.159 Z6.734 A90.931 B221.736
X199.976 Y-84.168 Z8.957 A91.268 B221.965
X199.976 Y-82.159 Z11.181 A91.631 B222.265
X199.976 Y-80.137 Z13.393 A92.026 B222.642
X199.976 Y-77.824 Z15.884 A92.52 B223.168
X199.976 Y-75.833 Z17.99 A92.987 B223.707
X199.976 Y-73.753 Z20.145 A93.521 B224.362
X199.976 Y-71.493 Z22.429 A94.163 B225.187
X199.976 Y-69.201 Z24.676 A94.883 B226.156
X199.976 Y-67.029 Z26.734 A95.636 B227.208
X199.976 Y-64.452 Z29.075 A96.622 B228.643
X199.976 Y-62.263 Z30.971 A97.543 B230.038
X199.976 Y-59.855 Z32.869 A98.6 B231.705
X199.976 Y-57.592 Z34.695 A99.773 B233.64
X199.976 Y-54.969 Z36.575 A101.194 B236.089
X199.976 Y-52.471 Z38.209 A102.63 B238.747
X199.976 Y-49.898 Z39.72 A104.218 B241.846
X199.976 Y-46.791 Z41.296 A106.258 B246.113
X199.976 Y-44.039 Z42.448 A108.155 B250.386
X199.976 Y-41.403 Z43.322 A109.991 B254.904
X199.976 Y-39.473 Z43.811 A111.287 B258.451
X199.976 Y-37.513 Z44.171 A112.516 B262.237
X199.976 Y-35.531 Z44.389 A113.631 B266.229
X199.976 Y-33.268 Z44.451 A114.695 B270.951
X199.976 Y-31.269 Z44.332 A115.401 B275.227
X199.976 Y-29.285 Z44.047 A115.845 B279.55
X199.976 Y-27.171 Z43.556 A116.002 B283.95
X199.976 Y-25.254 Z42.952 A115.85 B287.586
X199.976 Y-22.457 Z41.823 A115.088 B292.319
X199.976 Y-20.105 Z40.666 A113.911 B295.42
```

Figure 3.5-13 - Output from MasterCAM with modified generic 5-axis post processor

Once the data has been post processed with the modified post processor, it is saved as a .TXT file and imported into a specially designed Excel spreadsheet. The spreadsheet effectively prepares the data for direct use in RobotWorks. The following operations are performed on the imported data within the spreadsheet:

- The letters in front of the coordinate values are stripped out (eg. X199.976 → 199.976).
- The 'A' coordinates have 90º added to them and are then multiplied by -1.

- The 'C' coordinates (rotations about the 'z' axis) are set to a constant value (usually 0).

Figure 3.5-14 shows a sample of the spreadsheet. The raw tool path data generated by the modified MasterCAM post processor is exported into the columns under the heading 'Raw Data'. The spreadsheet then performs the aforementioned operations, yielding the columned data under the heading 'Processed Data'. The processed data can then be directly used in RobotWorks.

Raw data imported here from text file of tool path

Processed data which has been transformed ready for use in RobotWorks

Raw Data					→	Processed Data					
x	y	z	A	B		x	y	z	A	B	C
X199.976	Y-120.358	Z-1.751	A90.	B221.446		199.976	-120.358	-1.751	-180	221.45	0
X199.976	Y-112.862	Z-8.37	A90.	B221.446		199.976	-112.862	-8.37	-180	221.45	0
X199.976	Y-105.366	Z-14.989	A90.	B221.446		199.976	-105.366	-14.989	-180	221.45	0
X199.976	Y-92.125	Z0.	A90.	B221.446		199.976	-92.125	0.	-180	221.45	0
X199.976	Y-90.139	Z2.248	A90.302	B221.478		199.976	-90.139	2.248	-180.3	221.48	0
X199.976	Y-88.151	Z4.494	A90.611	B221.574		199.976	-88.151	4.494	-180.61	221.57	0
X199.976	Y-86.159	Z6.734	A90.931	B221.736		199.976	-86.159	6.734	-180.93	221.74	0
X199.976	Y-84.168	Z8.957	A91.268	B221.965		199.976	-84.168	8.957	-181.27	221.97	0
X199.976	Y-82.159	Z11.181	A91.631	B222.265		199.976	-82.159	11.181	-181.63	222.27	0
X199.976	Y-80.137	Z13.393	A92.026	B222.642		199.976	-80.137	13.393	-182.03	222.64	0
X199.976	Y-77.824	Z15.884	A92.52	B223.168		199.976	-77.824	15.884	-182.52	223.17	0
X199.976	Y-75.833	Z17.99	A92.987	B223.707		199.976	-75.833	17.99	-182.99	223.71	0
X199.976	Y-73.753	Z20.145	A93.521	B224.362		199.976	-73.753	20.145	-183.52	224.36	0
X199.976	Y-71.493	Z22.429	A94.163	B225.187		199.976	-71.493	22.429	-184.16	225.19	0
X199.976	Y-69.201	Z24.676	A94.883	B226.156		199.976	-69.201	24.676	-184.88	226.16	0
X199.976	Y-67.029	Z26.734	A95.636	B227.208		199.976	-67.029	26.734	-185.64	227.21	0
X199.976	Y-64.452	Z29.075	A96.622	B228.643		199.976	-64.452	29.075	-186.62	228.64	0
X199.976	Y-62.263	Z30.971	A97.543	B230.038		199.976	-62.263	30.971	-187.54	230.04	0
X199.976	Y-59.955	Z32.869	A98.6	B231.705		199.976	-59.955	32.869	-188.6	231.71	0

Figure 3.5-14 - Excel spreadsheet to prepare tool path data for RobotWorks

3.5.2.4 Simulation and Robot Control Program Creation with RobotWorks

The following steps are taken to produce a programmed robot cutting path from the post processed data generated in MasterCAM and prepared in the Excel spreadsheet.

1. The SolidWorks assembly containing the Kuka KR6/2 robot and cutting tool is opened. The assembly has two configurations; one has a 25 mm roughing tool mounted while the other has an 8 mm finishing tool mounted. The desired configuration is chosen depending on whether a roughing pass or finishing pass is to be simulated. It should be noted that the tool length is the critical parameter, since it defines the TCP which is traced along the tool path in RobotWorks to generate the robot control program.

2. The robots' kinematics file is loaded.

3. The prepared tool path data is highlighted in the Excel spreadsheet and copied. The data is then pasted into the RobotWorks 'Import Points to Path' user form shown on the left in figure 3.5-15. This is achieved by clicking the 'Read Lines' button on the user form. Alternatively the data in the spreadsheet can be saved as a .TXT file and read directly into the form provided the 'File Type' drop down box is set to 'Text Format XYZABC'. As can be seen in the figure, the data appears in the window along with an indication of the total number of path points (the imported path in figure 3.5-15 has 943 points).

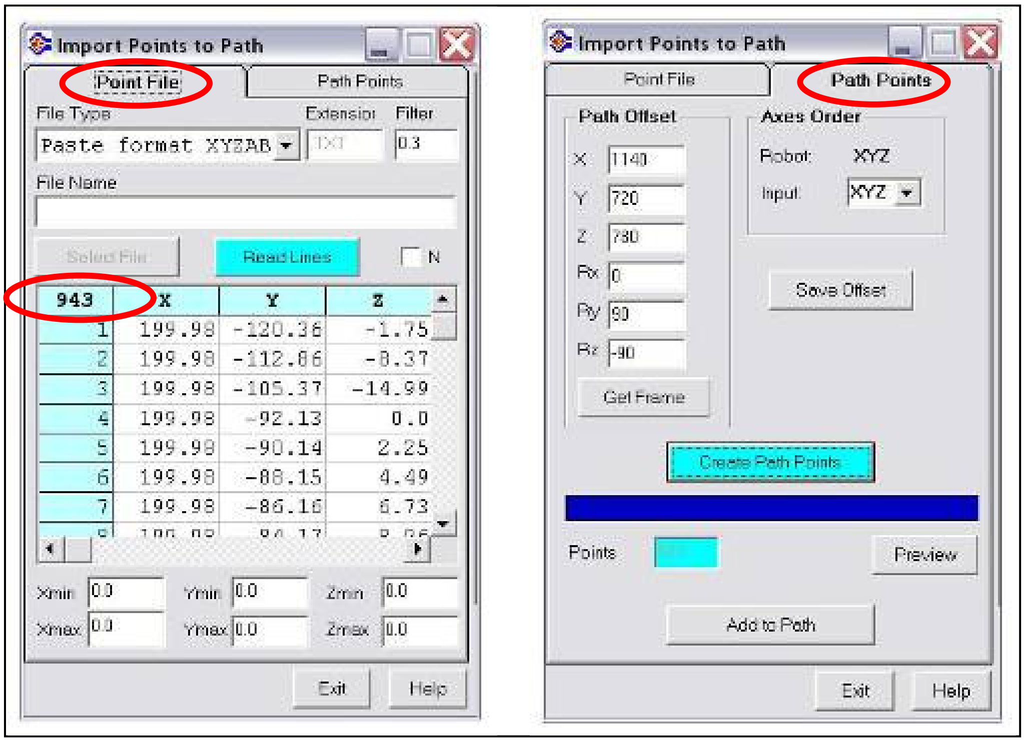

Figure 3.5-15 - Importing path points from Excel spreadsheet

4. The next step involves locating and orientating the tool path in the workspace. If the imported path was inserted without accomplishing this step, it would get inconveniently located at the origin of the SolidWorks assembly which is at the base of the robot. The location and orientation of the tool path's origin relative to the robot's coordinate system origin can be altered by filling in the 'Path Offsets' as shown in the right hand user form in figure 3.5-15. The values can be altered to match a particular physical mounting setup or more importantly to position the path so all the

points along the path can be physically reached by the robot. Figure 3.5-16 graphically explains the x, y and z path offsets.

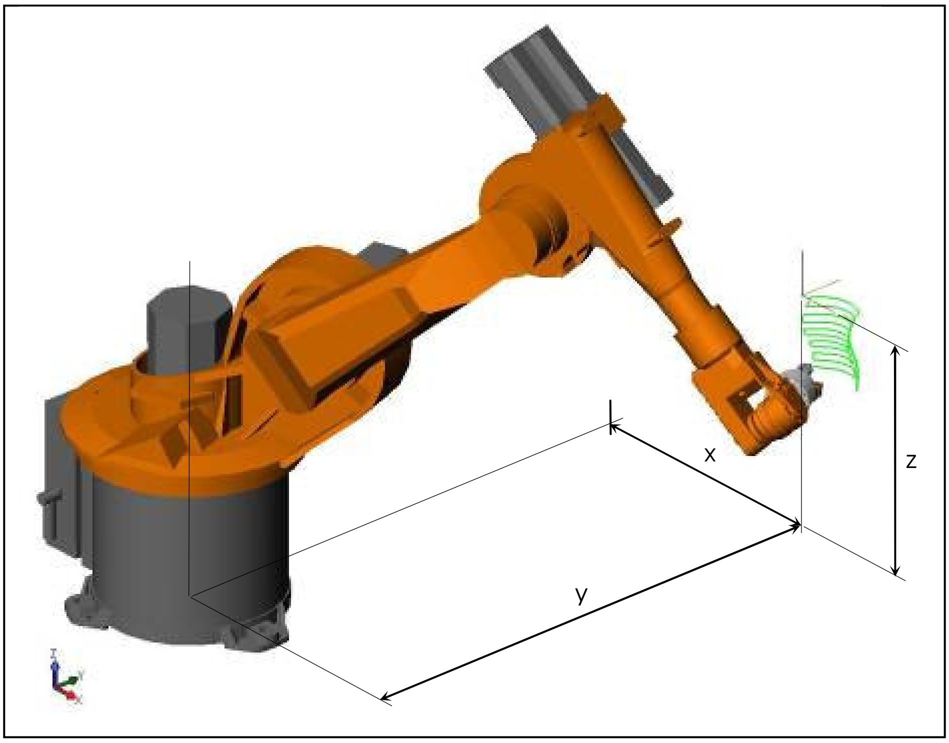

Figure 3.5-16 - Path location and orientation with respect to robot coordinate system

5. Once the path has been imported and the offsets have been set, the path can be previewed before it is loaded into a RobotWorks job. This is accomplished by clicking the 'Preview' button on the right hand user form in figure 3.5-15. Provided the path is as desired, it can be added to the RobotWorks job by clicking the 'Add to Path' button. Figure 3.5-17 shows a roughing path which was loaded into a RobotWorks job.

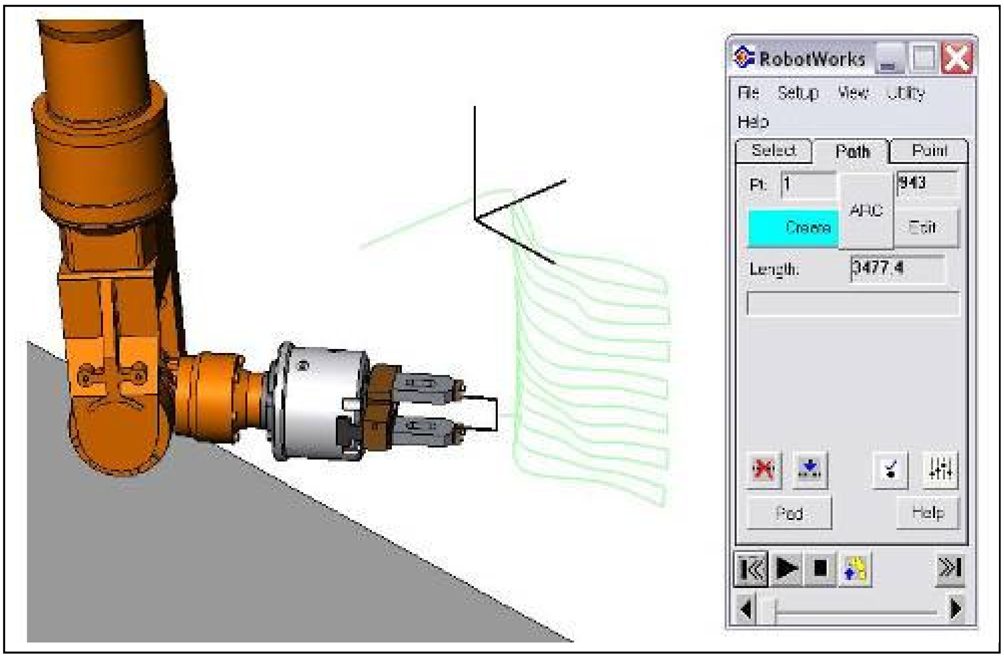

Figure 3.5-17 -Path creation from imported points in RobotWorks

6. Once the path has been loaded into the RobotWorks job, it can be simulated to check that all the points along the path are within reach. This is achieved dynamically on screen with the tool attached to the robot. The simulation stops if a robot joint limit is violated. Figure 3.5-19 shows a screen print of the simulation in process. The figure shows the joint limits 'Control Pad' which provides the user with real time axis position values. Also shown is the collision detection function described in the next step. If the robot can reach all the points along the entire path and the location of the path is in a position that would allow the foam blank to be physically mounted, the procedure is continued. However, if the robot cannot reach all the points (i.e. joint limit violations encountered), the path must be re-orientated and positioned until all the points on the path can be reached. Alternatively, individual limit violating points can be edited using the 'Control Pad' shown in figure 3.5-19. This does however alter the tool orientation at those points which can result in the sculpted surface not being as accurate as it could be.

7. The next step is to check for collisions between the blank and the tool (less the blade). To achieve this, a CAD model of the surface's bounding box (essentially the foam blank) is required. This can be easily created in SolidWorks during the CAD model generation step. The CAD model of the foam blank is brought into the SolidWorks assembly and referenced by its top front left corner to the tool paths origin as previously defined in the 'Path Offsets' input. A reference frame (coordinate system) is then added to the top front left corner of the blank in the SolidWorks assembly. This is achieved using the 'Create Frame in Robot World' user form shown in Figure 3.5-18.

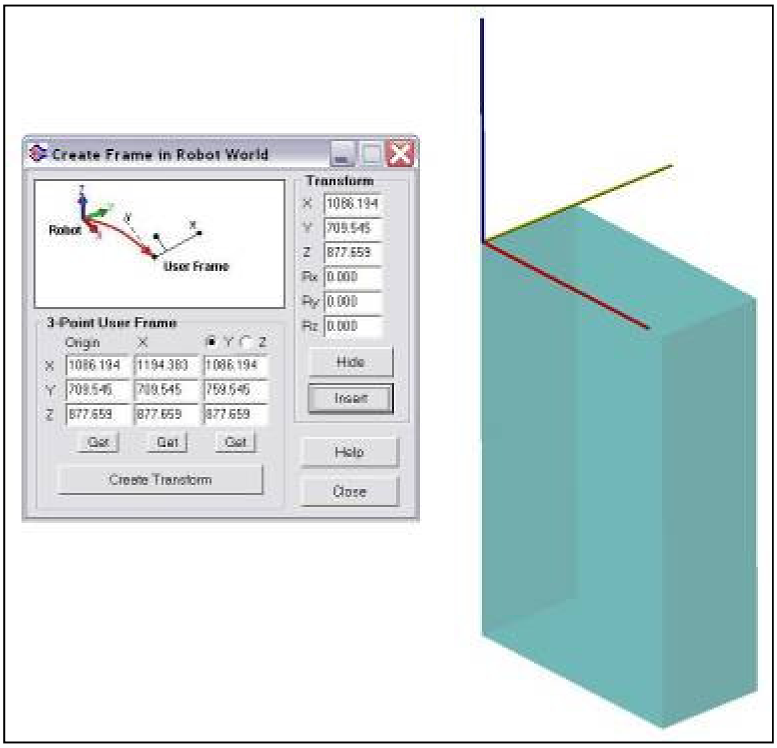

Figure 3.5-18 - Adding a reference frame in RobotWorks

Once the reference frame has been created, it is added to the RobotWorks job. All outputted Robot control commands will now be relative to the created reference frame. The path can now be simulated again, this time checking for collisions between the uncut stock and the tool (less the blade). As previously mentioned figure 3.5-19 shows a 'screen print' of the SolidWorks/RobotWorks working environment during the path simulation and collision detection check. At the time of the screen print, the programs were in the process of running the tool along the defined path (TCP trail visible). As shown in the user-form entitled 'Setup Interference', the tool (less the blade) has been selected as the 'moving part' while the blank has been selected as the 'fixed part'. The user-form entitled 'RobotWorks' contains the main controls for the RobotWorks program, whereas the user-form below it entitled 'Control Pad' shows the positional values for each of the robot's six axes. The simulation is automatically paused when there is a collision between the designated items or any one of the axis limits are exceeded (axis limits should not be violated as they have already been checked once). The collision of the tool (less the blade) with the blank indicates that a second roughing pass may be needed.

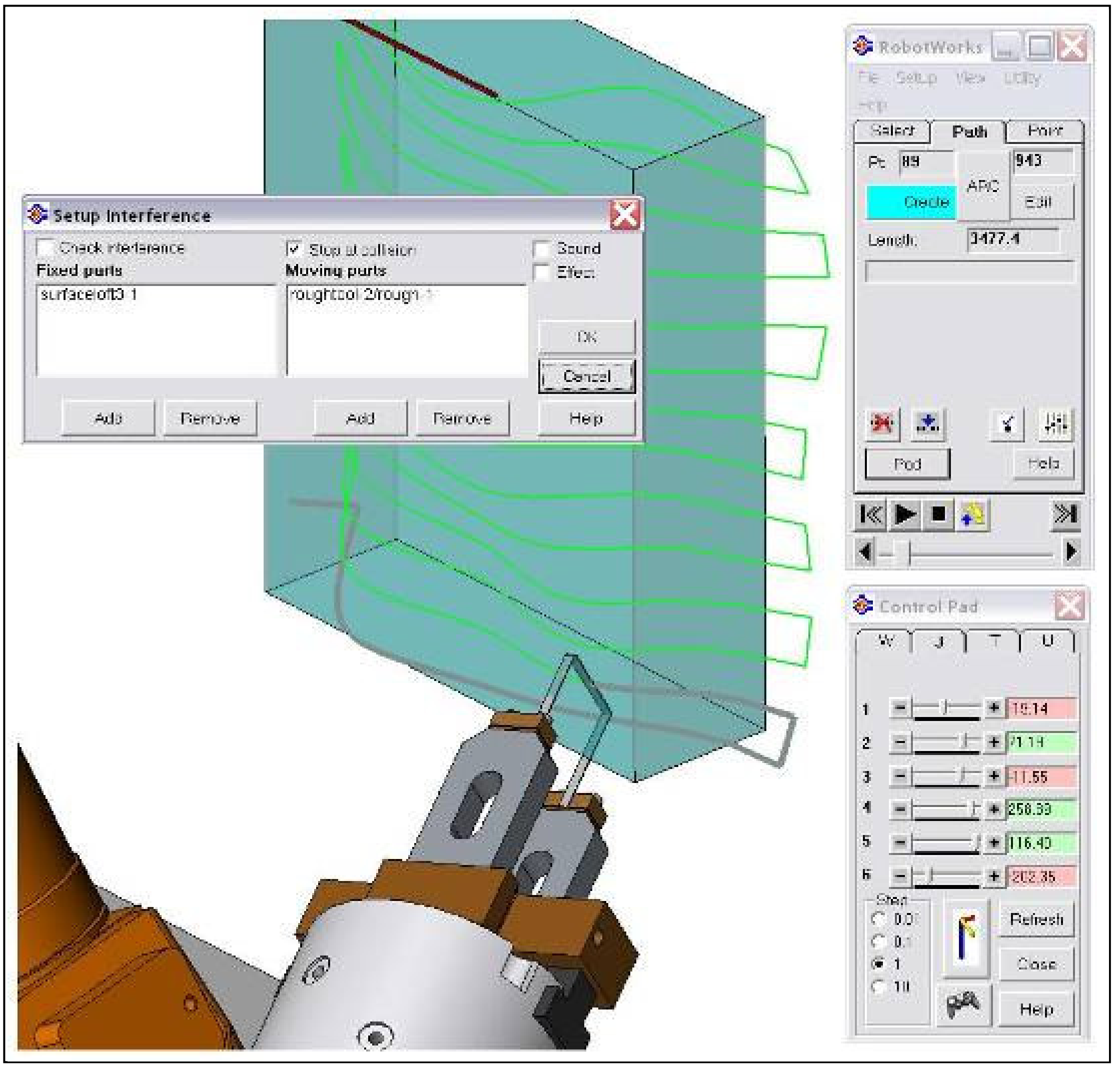

Figure 3.5-19 - Collision detection and axis limit check in RobotWorks

8. Once a successful simulation has been run, the points are converted into the native KUKA language. All the outputted commands are with respect to the chosen reference frame.

Generally, one roughing path and one finishing path are generated. If multiple roughing paths are required, the reference co-ordinate system can be shifted (leaving the blank where it is) to offset the cutting surface (this is explained in the next section). A typical roughing path generated using the newly developed procedure has around 900 -1000 points whereas a finishing pass can have up to 6000 points.

3.5.2.5 Setup and Implementation

The setup and implementation procedure was basically the same as for the preliminary 3D sculpting experimental work. The only exception was the incorporation of multiple roughing passes (see step 5 below). The setup and implementation procedure is given again below for completeness.

1. In order to efficiently transfer the generated control program to the robot's control PC, a code template is used. The template includes pre-written code to define robot velocities, coordinate systems, and 'return to home' speeds and motions. The code generated by RobotWorks is simply copied and pasted into the template.

2. The prepared control program is transferred to the control PC via a 3.5" floppy disk.

3. To ensure no surprises, the program is first executed in free air at 30% velocity with no foam blank mounted.

4. Provided the program runs as intended, the foam blank is then referenced and mounted. To aid in the referencing of the foam blank, the base coordinate system is programmed in RobotWorks to the top left corner of the blank as previously explained. The foam blank is temporarily mounted and the robot is commanded to go to the top left corner of the blank with the command: 'PTP {X 0, Y 0, Z 0, A 0, B 0, C -90}'. If the tool tip does not align with the top left corner of the blank, the table and/or blank are manually moved into position. The tool is then traversed around the perimeter of the front face of the blank to check alignment in all planes. Once the correct spatial alignment is confirmed the blank is secured in place via four coarse screws which grip the sides of the block.

5. If multiple roughing passes are required, the base coordinate system is shifted back the required amount. Shifting the base coordinate system has the effect of offsetting the entire surface. The amount is determined by firstly calculating the total depth of cut (i.e. the distance of the lowest point on the surface below the front face of the foam blank). The roughing tool is capable of removing up to 20 mm of material in one pass. Keeping in mind that 10 – 12 mm of material is left for the finishing pass to remove, the number of roughing passes can be easily determined. Hence, the base coordinate shift can be determined. Figure 3.5-20 shows a surface to be sculpted with the foam blank overlaid which is used to determine the total depth of cut and hence the number of roughing passes required.

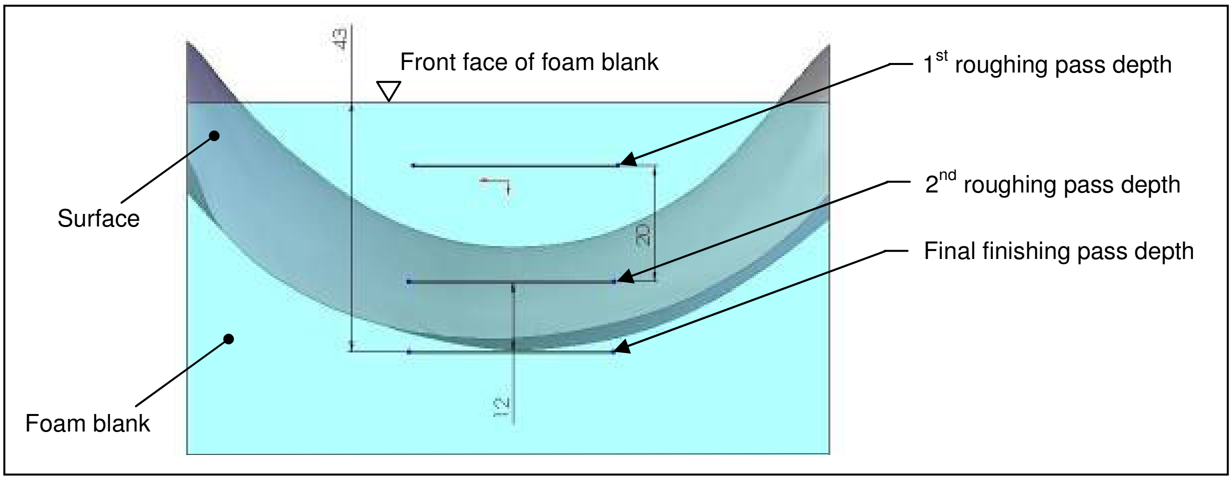

Figure 3.5-20 - Determining the number of roughing passes required

Once the number of roughing passes required is known, the base coordinate system can be shifted accordingly for each pass. Figure 3.5-20 can be used as an example. The base coordinate system for the path is initially set on the top left corner of the front face of the foam block. Both the roughing and finishing passes are programmed to cut the exact surface relative to the base coordinate system (i.e. if the coordinate system was left as is, the roughing pass would attempt to remove all the material right down to the finish surface in one go). For the first roughing pass the base coordinate system would be shifted out 32 mm (12 mm + 20 mm). For the second roughing pass the base coordinate system would be shifted out only 12 mm. And for the final finishing pass, the base coordinate system would be left unchanged from its original position. The base coordinate system is changed by altering the base coordinate system definition line at the beginning of the control program.

6. Once the base coordinate system has been adjusted for the particular pass, the DC power supply is turned on and the current is adjusted via the manual rotary switch. The current level is set based on past cutting experience and feel (a piece of foam is run through the heated blade by hand).

7. An extractor fan to remove the fumes is switched on and the control programs are executed.

3.5.3 Procedure Implementation and Results

In order to assess the efficacy of the newly developed procedure, two tests were performed. The two tests stemmed from the two different methods of producing CAD models outlined in section 3.5.2.1 of the procedure. The first test used an arbitrary CAD model produced from scratch in SolidWorks as the process input whereas, the second test utilised 3D scanner data from a real life surface to aid the generation of the CAD model. The two tests are now explained and their results presented.

3.5.3.1 Test 1 – CAD model Generated from Scratch in SolidWorks

The five step procedure outlined in section 3.5.2 was followed to produce the sculpted foam artefact represented by the CAD model in figure 3.5-21.

The CAD model for this test was created in SolidWorks by lofting over five arbitrary profiles. The profiles were created using a spline creation tool. Each profile was created on a plane 50 mm offset from the adjacent plane. The CAD model was saved in the IGES format as a complete continuous surface.

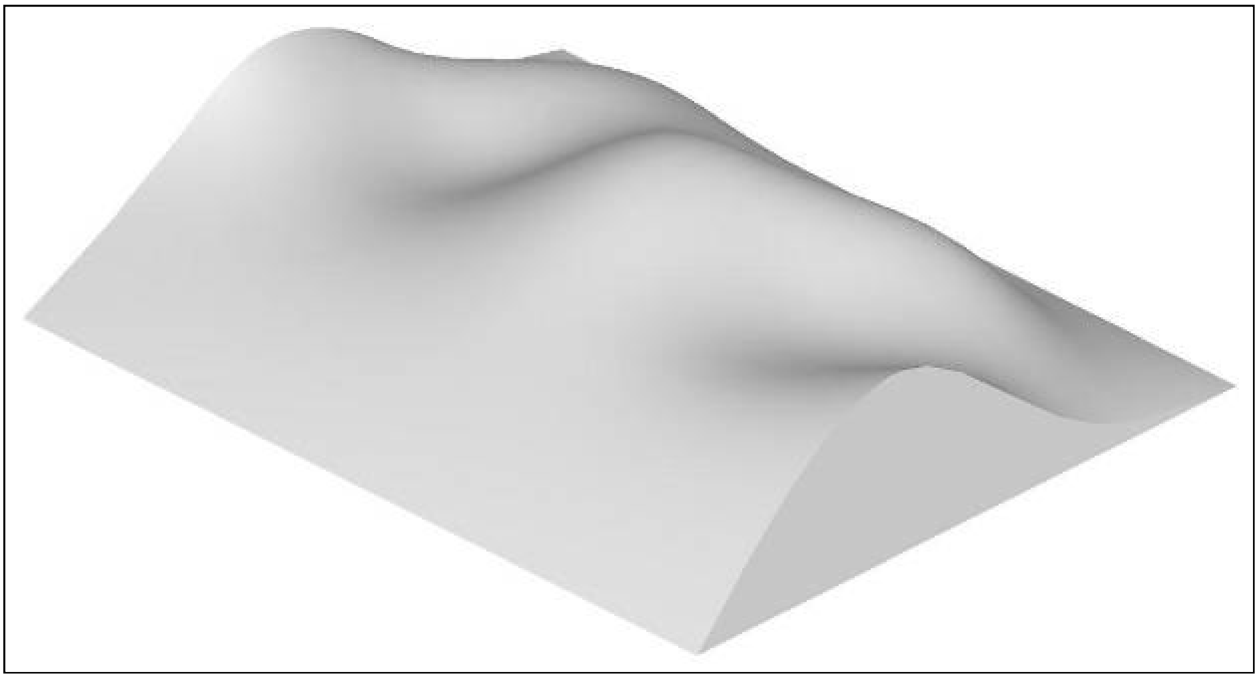

Figure 3.5-21 - CAD model used for test 1

As can be seen, the model was relatively arbitrary and comprised a relatively equal amount of concave and convex regions. A solid body was added for visual comparison with the final sculpted artefact (it is not required for any technical procedure). The size of the foam blank required for the model was 160 mm x 190 mm x 50 mm.

The IGES CAD model was opened within the MasterCAM environment in order to generate and optimise the required tool paths. The parameters and options chosen for the tool path generation and optimisation step are listed and explained below:

- The roughing pass was to be achieved with a 25 mm square ended blade. The roughing pass comprised a simple parallel bi-directional path with a spacing of 16 mm and extensions (model edge over runs) of 20 mm. The 16 mm path spacing was chosen to yield adequate overlap and produce minimal cutting forces throughout the roughing procedure which was to be accomplished at a velocity 0.1 ms^{-1}. The 20 mm extensions were used to ensure a clean cut at the edges of the model.

- The finishing pass was to be achieved with an 8 mm flat ended blade with tapered legs as shown in figure 3.5-22 below. The taper was used to strengthen the blade against lateral cutting forces.

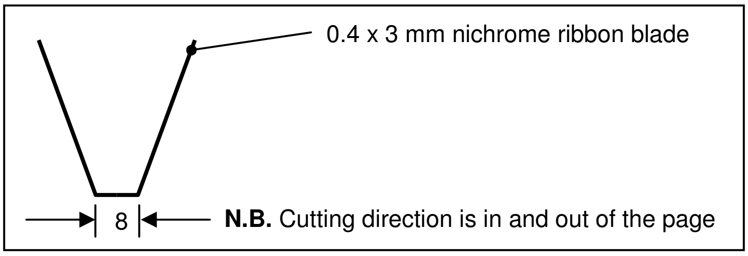

Figure 3.5-22 - Finishing blade profile used for test 1

The finishing pass comprised a parallel bi-directional path with a spacing of 6 mm and extensions of 20 mm. The 6 mm spacing was chosen to minimise the cusp between successive passes as well as minimising the overlap. A spacing of 8 mm would have resulted in no overlap but significant cusp. The 20 mm extensions were chosen for the same reason as in the roughing pass.

The rouging pass and finishing pass were both generated on the exact surface with no offsets applied. The offsets for the rouging pass/es were later applied by moving the base coordinate system as explained in section 3.5.2.5 of the procedure. The roughing and finishing paths produced in MasterCAM are shown in figures 3.5-23 and 3.5-24 respectively.

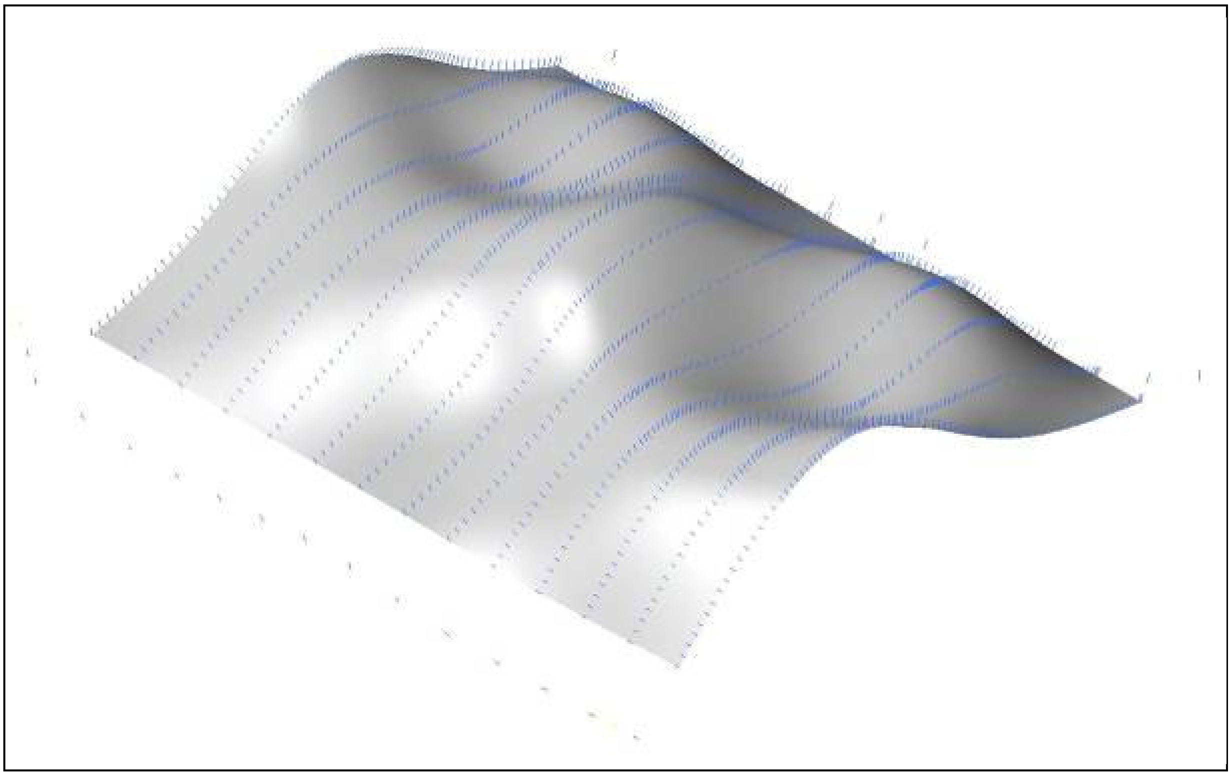

Figure 3.5-23 - Roughing path generated in MasterCAM

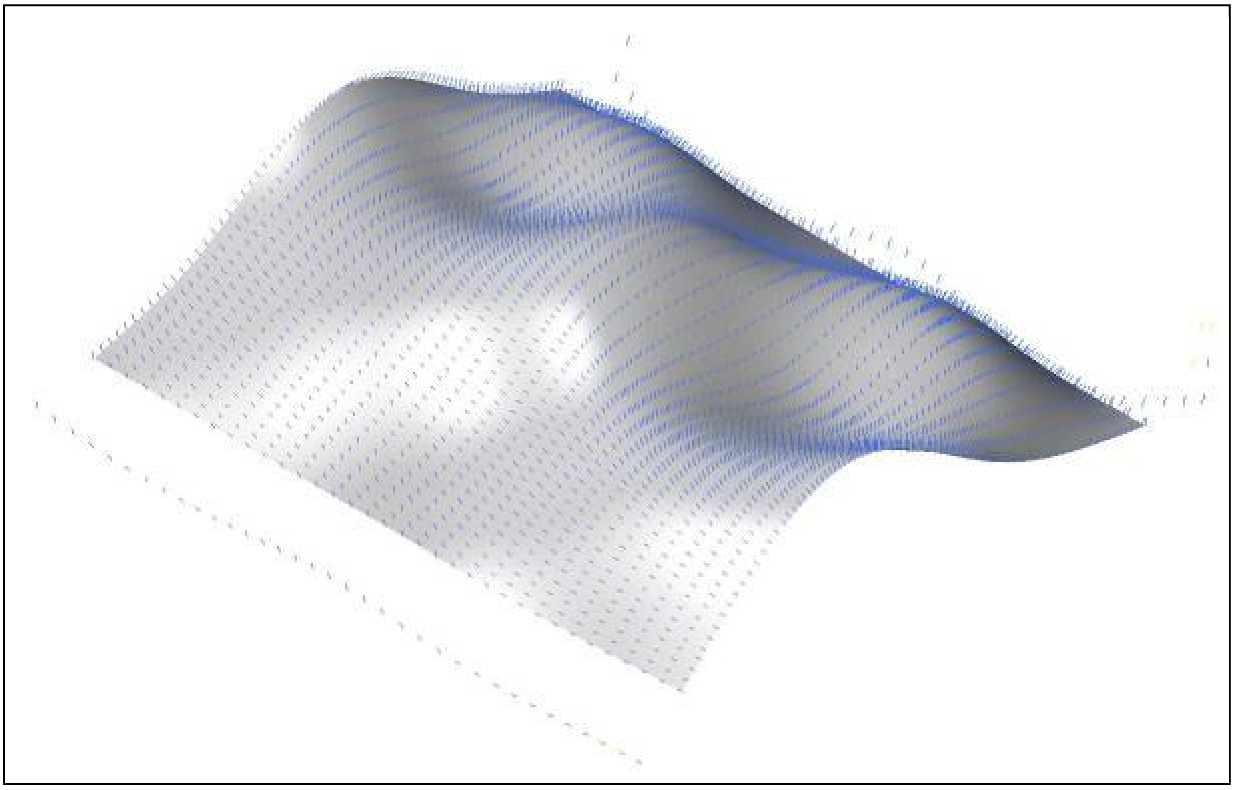

Figure 3.5-24 - Finishing path generated in MasterCAM

Both the roughing and finishing passes were outputted using the modified 5-axis post processor. They were then imported into the specially designed excel spreadsheet, transformed and imported into RobotWorks/SolidWorks for simulation and Kuka control program generation. The tool path was aligned so that the cutting would be horizontal and would progress from bottom to top. This was done so the swarf would fall off under gravity instead of requiring manual removing. The Kuka control program for the roughing pass contained around 1000 points whereas, the control program for the finishing pass contained 2400 pts.

The setup and implementation was followed as per the procedure. Due to the fact that the model to be sculpted had no flat sides to screw into, the blank was glued to another block of foam which was screwed to the mounting fixture. The thickness of the block was chosen to allow clearance between the tool and the mounting fixture at either end of the passes. The total depth of cut was around 40 mm hence necessitating the use of two roughing passes. The first roughing pass was achieved by offsetting the base coordinate system 30 mm. The second pass required an offset of 10 mm and the final finishing pass obviously required no offset.

Figure 3.5-25 shows the sculpted artefact.

Figure 3.5-25 - Sculpted artefact from test 1

As can be seen, the artefact was successfully sculpted from EPS foam. It should be noted that the foam blank was cut a little shorter than the CAD model and as a result, the sculpted artefact does not contain all the geometry shown in figure 3.5-21. The times taken to achieve each step in the 5 step procedure are listed in table 3.5-1 along with a break up for each step where appropriate.

Table 3.5-1 - Procedure times for test 1

Step 1 – CAD Model Generation	
Total time =	5 minutes
Step 2 – Tool Path Generation	
Roughing pass generation time =	5 minutes
Finishing pass generation time =	1 minutes
Step 3 – Post Processing	
Total time =	1 minute
Step 4 – Simulation and Kuka File Creation	
Roughing simulation and file creation time =	10 minutes
Finishing simulation and file creation time =	15 minutes
Step 5 – Setup and Implementation	
Dry run time =	3.05 minutes
Blank referencing time =	5 minutes
Roughing time (2 x roughing passes) =	1.7 minutes
Finishing time =	2.2 minutes
Total Process time =	**48.95 minutes**

A discussion of the process and the physical results from test 1 and 2 is presented in section 3.5.4 shortly.

3.5.3.2 Test 2 – Practical Application Using 3D Scanner

In the field of Medical Radiation Therapy, various bodily supports are used to hold and align the patient in position for treatment. One particular support used is the head and neck rest which supports the patients head and neck while in the supine position. Usually there are only 5 different supports to suit various sizes and shapes. Typically a patient will receive treatment over several sessions. Each time the patient is treated they must be located in exactly the same position to ensure the radiation treatment is administered to the same location. A patient customised head and neck support would improve the reproducibility of the patient's position for each treatment which, in turn would increase the accuracy of patients treatment. Additionally the time involved with aligning the patient for each treatment would also be reduced.

The second test involved sculpting a patient customised radiation therapy head and neck support. The FastScan 3D scanner was used to scan the back of the authors head and neck. In order to obtain a smooth surface, a swimming cap was worn. The acquired data was then processed to produce a uniformly spaced set of point cloud data. The specially designed Matlab program then created 14 cross section slices which were imported into SolidWorks and lofted over to re-create an IGES surface. The surface was then trimmed to have straight edges. The un-trimmed and trimmed surfaces are shown in figure 3.5-26.

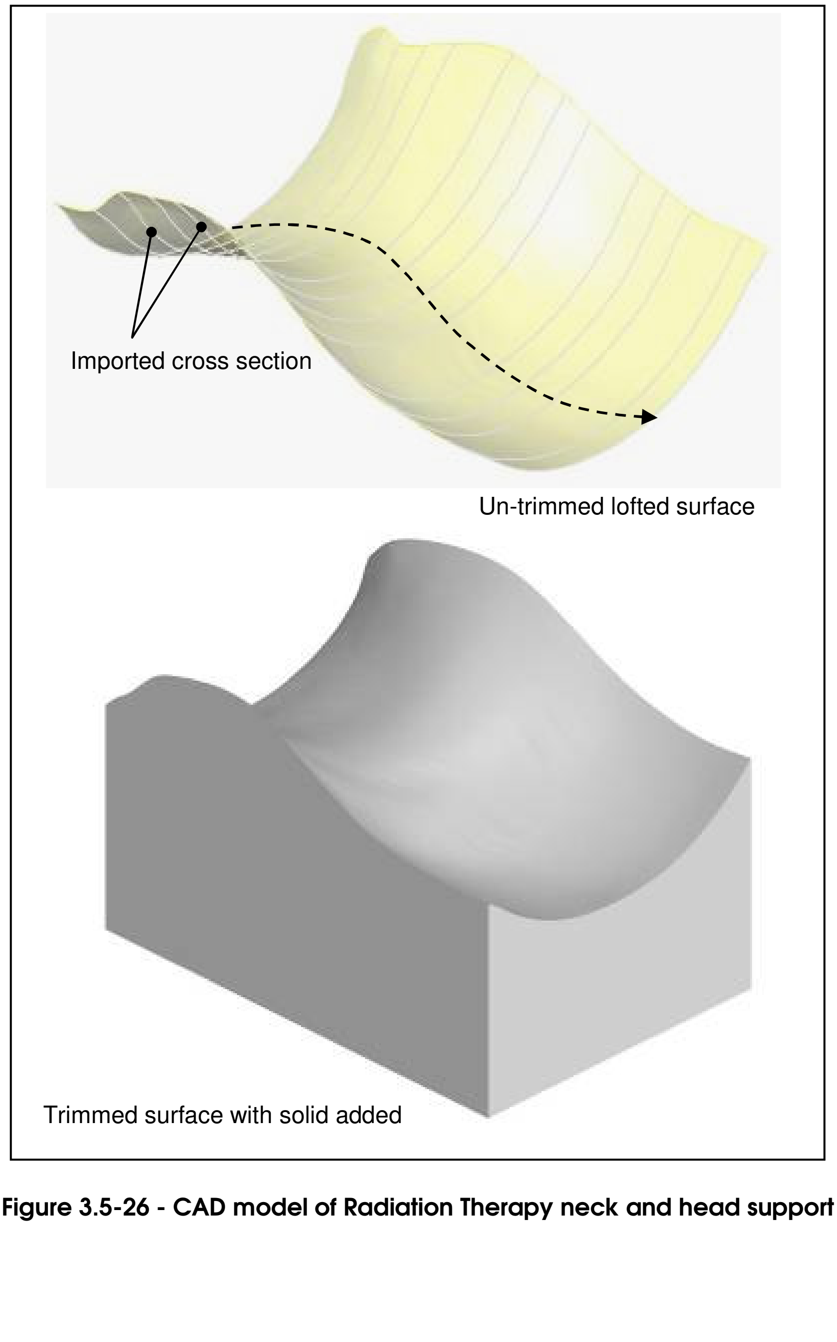

Figure 3.5-26 - CAD model of Radiation Therapy neck and head support

As can be seen the surface was predominantly concave with rather steep sides. A solid body has been added for visual comparison with the final sculpted artefact (it is not required for any technical procedure). The size of the foam blank required for the model was 110 mm x 160 mm x 110 mm.

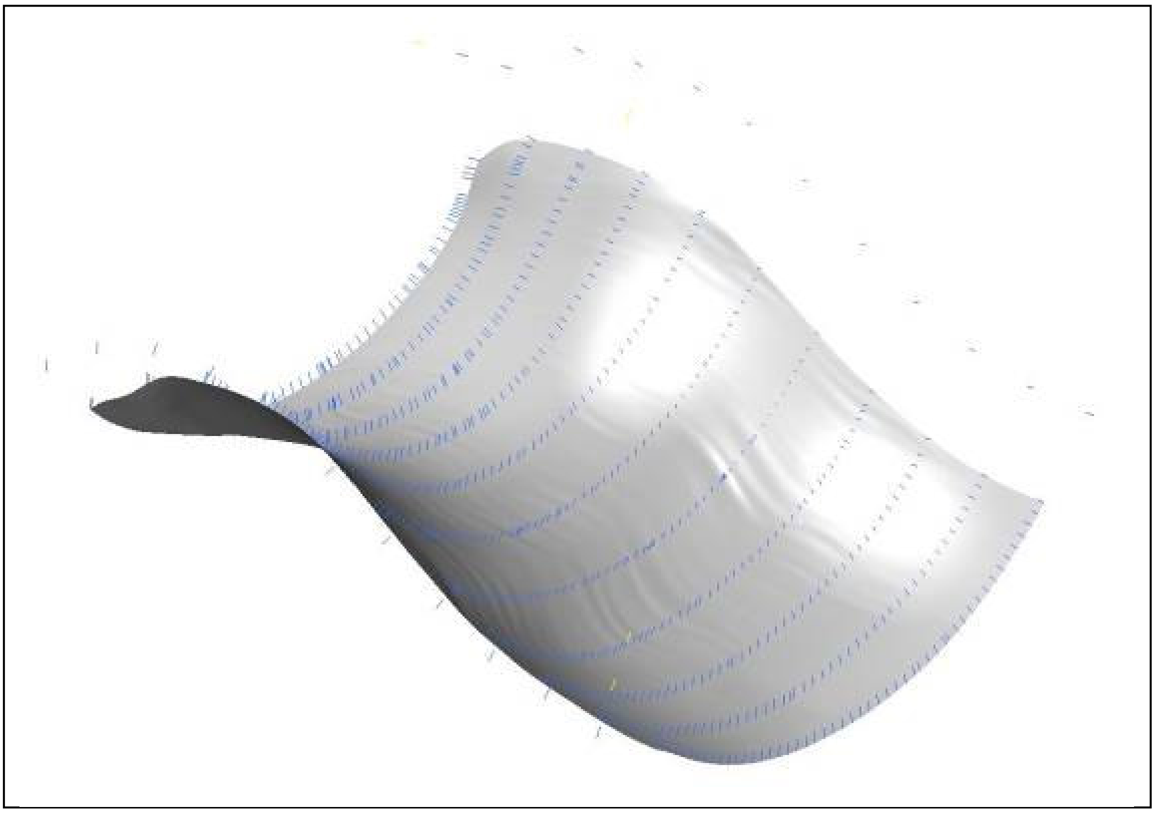

Figure 3.5-27 - Roughing path generated in MasterCAM

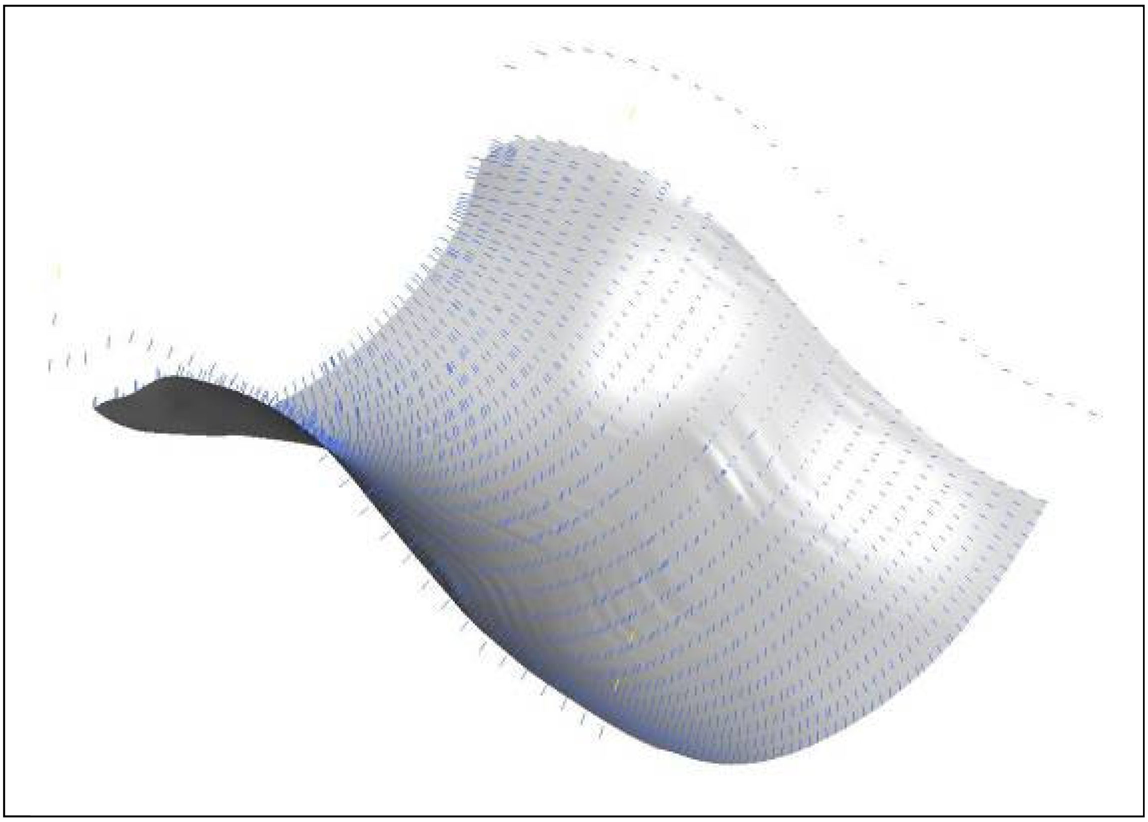

Figure 3.5-28 - Finishing path generated in MasterCAM

The IGES CAD model was opened within the MasterCAM environment in order to generate and optimise the required tool paths. The parameters and options chosen for the tool path generation and optimisation step were the same as for test 1 and were chosen for the same reasons. The same tools were also used for the roughing and finishing passes. The roughing and finishing paths produced in MasterCAM are shown in figures 3.5-27 and 3.5-28 respectively.

The post processed and transformed roughing and finishing passes were imported into RobotWorks/SolidWorks and were again aligned so the cutting would be accomplished horizontally from bottom to top to aid the swarf removal. The Kuka control program for the roughing pass contained around 650 points whereas, the control program for the finishing pass contained 1200 pts.

The total depth of cut for the head and neck support was around 60 mm and therefore required a total of three roughing passes. The base coordinate system was shifted 44 mm for the first roughing pass (i.e. the first roughing pass removed 16 mm of material (60 – 44 = 16)). The second and third roughing passes required respective shifts of 27 mm and 10 mm. The final finishing pass obviously required no base coordinate system shift which removed 10 mm of material.

Figure 3.5-29 shows the sculpted head and neck support.

Figure 3.5-29 - Sculpted medical radiation therapy treatment head and neck support

As can be seen the head and neck support was successfully sculpted out of EPS foam. The times taken to achieve each step in the 5 step procedure are listed in table 3.5-2 along with a break up for each step where appropriate.

Table 3.5-2 - Procedure times for test 2

Step 1 – CAD Model Generation	
Scanning time =	5 minutes
Processing and manipulation time =	15 minutes
CAD model re-creation time =	15 minutes
Step 2 – Tool Path Generation	
Roughing pass generation time =	5 minutes
Finishing pass generation time =	1 minutes
Step 3 – Post Processing	
Total time =	1 minute
Step 4 – Simulation and Kuka File Creation	
Roughing simulation and file creation time =	10 minutes
Finishing simulation and file creation time =	15 minutes
Step 5 – Setup and Implementation	
Dry run time =	3.25 minutes
Blank referencing time =	5 minutes
Roughing time (3x roughing passes) =	2.25 minutes
Finishing time =	2.5 minutes
Total Process time =	**80 minutes**

A discussion of the process and the physical results from both test 1 and 2 is presented in the ensuing section.

3.5.4 Discussion of Results

The implementation of the developed procedure on the two tests, along with their results gave rise to several points which are discussed below:

- Using MasterCAM to automatically generate and optimise the tool path expedited the procedure substantially compared to the manual method used in the preliminary 3D sculpting trials. The generated paths could easily be modified and regenerated with just a few clicks of the mouse. The reason the time taken to generate the finishing pass was so much faster than that for the roughing pass, was because the generation of the finishing pass only required editing of the path spacing on the already generated roughing pass (see step 2 of table 3.5-2 for times). It should be noted that a finer finishing pass (i.e. 3 mm path spacing) could have easily been generated and implemented to improve the surface finish obtained.
- Because the tool paths were generated using a 5-axis path generation and optimisation package (MasterCAM), the tool could not be programmed to always be normal to the direction of travel, since this would require 6-axis control. This is not a problem when using a rotating milling cutter but becomes one when using the nichrome ribbon tools. To overcome this problem, parallel cutting paths were used and the tool rotation about its vertical axis was set at a constant angle (i.e. 6th axis set to a constant value), which was maintained during the entire path. Because the 6th axis was set

to a constant value, the tool did not perform 180º turns at the ends of each pass like in the preliminary 3D sculpting tests. Subsequently, the time between the end of one pass and the start of the adjacent pass was significantly reduced. Due to the reduced time, the blade did not increase in temperature nearly as much between exiting and entering the foam. This resulted in a more uniform surface finish due to less variation in blade temperature. Another positive effect of the constant 6th axis angle was the fact that alternate sides of the blade were used for cutting as opposed to just one side in the preliminary 3D sculpting tests. This resulted in the blade lasting longer before yielding. It is also postulated that the alternating side of cutting reduced the amount of molten material deposited from the blade during re-engagement with the foam.

- One very noticeable difference between the execution of test 1 and test 2 was in the smoothness of the robotically effected motion. The robot motion during the execution of test 1 was very smooth and consistent, while the motion during the execution of test 2 was somewhat 'bumpy' and erratic. The smooth motion of test 1 was a product of the smooth surface created by lofting over smooth profiles. It is postulated that the cross sectional slices produced by the Matlab program for test 2 contained small irregular protuberances. When the cross sections were lofted over, small surface ripples were created which were barely noticeable but affected the generated tool path substantially. It is surmised that the erratic robot motion was primarily due to the rapidly changing surface normals as illustrated by figure 3.5-30.

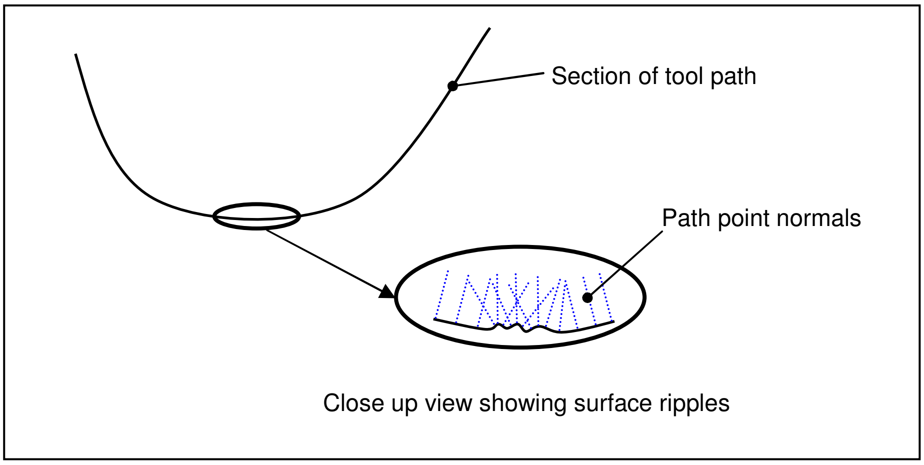

Figure 3.5-30 - Rapidly changing surface normals on rippled surface

The reason for the bumpy cross sectional slices was that the slicing algorithm was performed on the .TXT file representation of the model as opposed to the .STL file representation. Because a .STL file essentially consists of multitudes of tiny defined surfaces, the exact intersection of a cutting plane with the said surfaces can be determined, hence yielding smooth cross sectional slices (this is essentially what expensive RP slicing software does). The .TXT file representation was used because it was easier to manipulate and process. The Matlab slicing algorithm could not use single cutting planes to slice the .TXT file because it would be impossible to exactly intersect any points. Subsequently a 'slicing band' had to be used, the size of which could be varied. Typically a band width no greater than 1 mm was used. The Matlab slicing algorithm simply found all the data points that fell in the defined band centred on a certain 'x' value. Each point located within the band was then assigned that 'x' value. This is where the bumps were introduced. Figure 3.5-31 explains the concept.

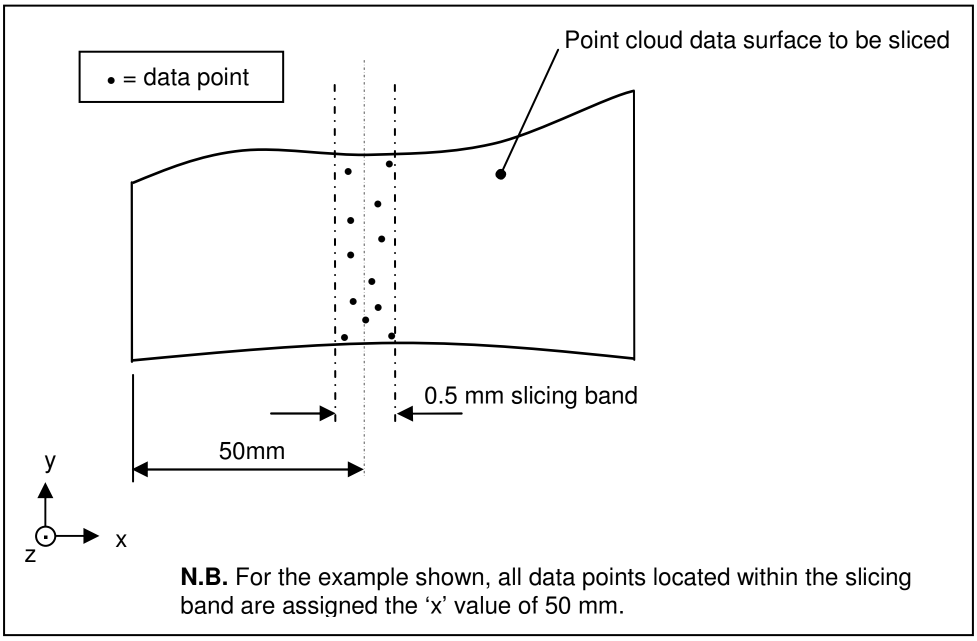

Figure 3.5-31 - Slicing of point cloud data to obtain cross sectional slices

As can be seen from figure 3.5-31, the bumps arose because the data points were forced into a cross section regardless of whether they actually coincided with the exact 'x' value of the cutting plane. One would think that reducing the slicing band would solve the problem; however, if the slicing band was too small, an insufficient number of points would be obtained to generate a complete cross sectional profile (it was found that a band of 0.5 mm barely generated enough points!). The Matlab slicing algorithm should be viewed as a temporary work around which was needed to successfully perform the testing and not as a permanent solution.

- The way in which the path was oriented to cut horizontally from bottom to top aided the swarf removal substantially. The swarf simply fell under gravity after being separated from the parent material. Even if a piece of swarf from one pass remained stuck to the stock it was always removed by the tool on the next pass. It is thought that the geometry of the tapered finishing tool aided this process. Swarf management is an important aspect in the foam sculpting process, since swarf that is not removed can be re-cut which inconveniently cools the blade and can also result in the deposition of molten material onto the already cut surface (hence creating surface defects).

- Table 3.5-1 and 3.5-2 show that a large proportion of the total time taken was associated with the simulation and control program creation step. For tests 1 and 2 this step accounted for 61% and 32% of the total time respectively. The only reason that the percentage was significantly smaller for the second test was that test 2's total time was substantially greater than that of test 1 due to its increased CAD model generation time (this is discussed in the next point).

  The reason for the simulation and control program step taking such a large proportion of time can be explained as follows. Once the path points are imported into RobotWorks, the path must be completely simulated. As previously mentioned this is performed dynamically on screen with the SolidWorks assembly of the robot and tool. What is seen on the screen is essentially what the robot will do in the actual cutting situation. Because the paths contain so many points (sometimes in the order of 1000's), the computer is subject to a high graphical and computational work load. It was common for the simulation of traversing the tool along the entire path to take up to 10 minutes.

The simulation is essential though, since the control program can only be created once the SolidWorks model of the robot and tool has successfully traversed the entire imported path. The simulation is used to compute the actual joint values of the robot at each point and hence create the control program.

- As can be seen from table 3.5-2, the CAD model generation time was substantially greater than the time required by test 1 (see table 3.5-1). The main portion of this time was involved with the 3D scanner and subsequent processing of the scanner data. It should be noted that the time taken can be considerably decreased (say to around 5 minutes) with practice and experience in using the scanner and associated software. The substantial CAD model re-creation time can also be decreased by using specially developed surfacing software which is available. It should also be noted that the time taken to generate a CAD model from scratch can take substantially longer than indicated in test 1 if the model is more complex. Typically a 3D scanner will offer substantial time savings by aiding the generation of complex CAD models.
- The actual physical setup and sculpting of the artefacts for tests 1 and 2 only took 12 minutes and 13 minutes respectively. This is extremely quick when compared to other processes such as RP (usually several hours at least) and traditional CNC milling.
- A unique problem experienced in the execution of test 2 was 'singularity'. Singularity is where the 4^{th} and 6^{th} axes align themselves, at which point, a small programmed linear motion can cause both axes to rotate in opposite directions at great speed in order to effect the said small motion. The linear speed had to be reduced at several singularity points so that the robot's axes motors would not exceed their velocity limits. Singularity can be avoided by careful positioning of the tool path in the workspace. The version of RobotWorks which was used does not perform an adequate singularity check and does not check for joint velocity limits at all.
- The final point to be made is also with regard to test 2. During the RobotWorks simulation it was evident that the clearance between the tool (less the blade) and the uncut stock and cut stock was very close. When the program was executed the simulation was proven correct. The electrical service wiring around the tool in actual fact collided with the stock and uncut stock at particular points along the path (the wiring was not included in the SolidWorks model). In addition, the robot's joints were extended very close to their limits in several areas along the path. These occurrences were obviously caused by the large total depth of cut and the rather steep regions of geometry particularly at the sloping sides of the neck portion. This point highlights the fact that the system is limited by the tool design and the fact that the tool must be kept normal to the surface it is sculpting at all times.

3.5.5 Advanced 3D Sculpting Conclusions

The two tests successfully resulted in the sculpting of two artefacts from EPS foam using the newly developed procedure. The first artefact was sculpted using a CAD model generated from scratch as the primary process input. The second test utilised a 3D scanner to produce point cloud data of a physical real life object, namely the head and neck of the author. The data was subsequently used to produce a CAD model of a user customised medical radiation therapy head and neck support which in turn was used as the primary input to the process. The following conclusions were made regarding the implementation of the newly developed procedure and the results obtained through the two tests.

- The Automation of the tool path generation and optimisation step through the use of MasterCAM significantly reduced the time and effort required compared to the method used in the preliminary 3D sculpting work.
- The efficient 5-axis tool paths produced smooth cuts (except for the erratic motion phenomenon experienced in test 2) and minimised the blade temperature variations by reducing the time between exiting and entering the foam.
- It was found that the generation of the tool path is very sensitive to small surface imperfections such as ripples caused when bumpy cross section profiles are used to create surfaces. The results were clearly visible through the erratic bumpy robot motion seen during test 2. This phenomenon highlighted the need to use specialised auxiliary software to create smooth IGES surfaces from 3D scanner point cloud data. E.g. Geomagic Studio.
- The actual setup and implementation step of the procedure was extremely fast in comparison to other processes such as RP and CNC milling. This indicated that if further time savings are desired they should be sought in the other four steps of the procedure.
- Test 2 highlighted several robot limitations which exist due to the fact that the sculpting tool must be maintained normal to the surface it is sculpting at all times. This requirement can push the robot's joints to their limits. Additionally, it was found that the alignment and orientation of the tool path in the workspace is not only important in terms of reach-ability but also in avoiding singularity.

Overall, the implementation of the advanced 3D sculpting procedure provided useful results. The ensuing section contains suggested future work and recommendations as a result of carrying out this research.

4 FUTURE WORK AND RECOMMENDATIONS

This section outlines several areas for future work and provides recommendations in light of the conducted research. The areas are: 'tool design and work piece mounting', 'system automation and integration', 'CAD model generation', 'tool path generation and post processing' and 'KUKA system issues'.

4.1 Tool Design and Work Piece Mounting

Several areas of future work are essential in the area of tool design and the manner in which the foam work pieces are mounted and located within the work space.

4.1.1 TCP → Tool Mounting Flange Distance

A common problem experienced throughout the testing was related to the tool's design and its inability to reach all the points along a programmed path without violating joint limits, velocity limits or succumbing to singularity. It became evident through the testing that the cause of the aforementioned problems was an excessive distance between the TCP and the tool mounting flange. The current tool setup comprises a pneumatic gripper, gripping fingers, tool base, element mounting blocks and the actual cutting blade. The distance from the TCP to the tool mounting flange on the current setup is 182 mm and 175 mm for the roughing and finishing configurations respectively. Because the tool mounting flange (6th axis of robot) is at such a distance from the TCP, small movements with large orientation changes at the TCP can result in excessively large movements at the tool mounting flange and robot joints. This concept is illustrated in figure 4.1-1.

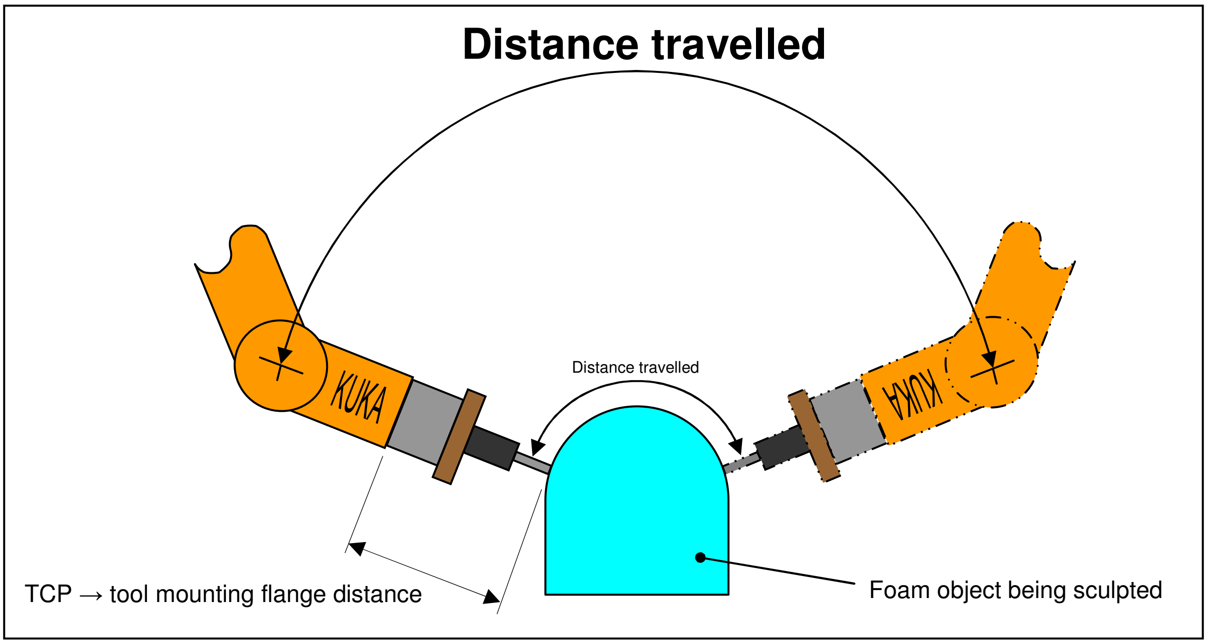

Figure 4.1-1 - TCP → tool mounting flange distance problems

As can be seen from figure 4.1-1, if the TCP travels a short distance but has a large orientation change, the robot linkages are forced to travel a large distance. Problems arise when the linkages cannot move fast enough to maintain the programmed velocity at the TCP which must be kept normal to the surface it is sculpting.

The excessive TCP → tool mounting flange distance also means the joint limits are often violated due to seemingly small movements at the TCP. It is therefore recommended that substantial future work be undertaken in the area of tool design. The ideal tool would be able to reach all the points along a programmed path and do so at a reasonable velocity (maximum of around 0.15 ms^{-1} at the TCP) without exceeding joint and velocity limits. Seeking to reduce the TCP → tool mounting flange distance would be an excellent first step along the path to realising an ideal tool. It should be noted however, that a trade off exists between tool length and the ability to sculpt difficult surface geometry where a long slender tool is advantageous.

4.1.2 Tool Power Cables and Air Supply Lines

The tool must be supplied with air for the pneumatic gripper and electrical power to heat the Nichrome blade. The air supply lines and power cables often became tangled or got in the way of the tool during manoeuvres. Currently, the setup does not allow the tool to rotate more than 360º, which often occurs during the motions between the robot's home position and the start and end of the path. Additionally the setup also prohibits spiral or circular type tool paths which can be useful on certain geometry. It is henceforth recommended that work be undertaken to mitigate this problem. A possible solution could look similar to conventional robotic spot welding 'swivels' which allow tangle free operation of spot welding heads. The swivel accommodates tangle free passages for air, water and electrical current. A typical spot welding swivel is shown in figure 4.1-2.

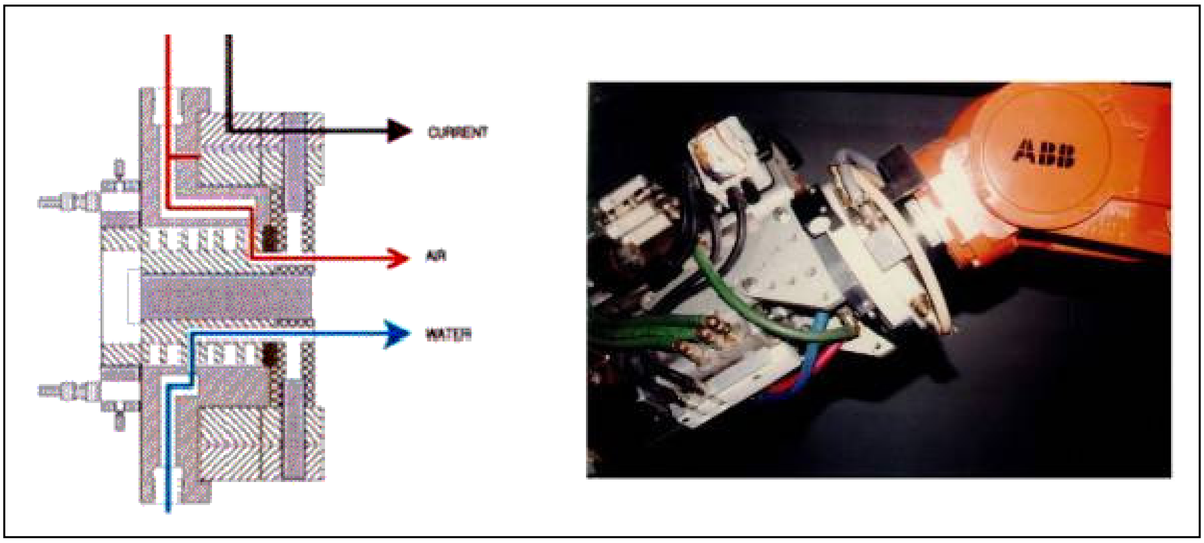

Figure 4.1-2 - A typical spot welding 'swivel'

A design to solve this tangling problem will possibly conflict with the solving of the aforementioned tool length problem. Careful concurrent consideration of both problems is therefore essential.

4.1.3 Tool Blade Design

Although the thermo-mechanics of foam sculpting is outside the scope of this research, it is worth noting here the possible future work which could be carried out in the area of tool blade design for optimum cutting performance. The extensive experimental work carried out highlighted the need for some careful innovative tool blade design. Currently, the tools are simple square ended profiles of differing sizes dependent on the path spacing applied. The design of the tool blade should consider the following:

- What blade profile yields the best/desired surface finish?
- Is nichrome ribbon the best material for the blade?
- Can the tool be designed to compensate for the 'weatherboard' surface finish effect (as explained in section 3.4.3.10)?
- Design for effective swarf management.
- Should there be dedicated blade sizes for particular path spacing, or can an 'adaptive' tool be designed (i.e. one tool does roughing, finishing and anything in between)?
- Is the design of a dedicated non-contact ablation tool similar to that used by Kim et al (28, 29) an option?

4.1.4 Work Piece Mounting

The mounting of the work piece in the work space is very important, since poor mounting can result in problems such as the robot not being able to reach all the points on the programmed path. The current work piece mounting setup is rather temporary, inflexible and cannot align the work piece to a satisfactory accuracy. A fixture must be designed which can hold a large number of different shaped and sized objects. Additionally, the work piece must be able to be positioned accurately in a broad range of different locations and orientations within the workspace.

A work piece mounting system worth some consideration is one which would incorporate an auxiliary axis. This axis could be either linear or rotational. Two strategies should be considered. The first would involve an auxiliary axis (either linear or rotational) which would manipulate the work pieces synchronously with the robots axes. For example, a 5-axis tool path could be split into 4 axes of control for the robot and 1 axis of control for the work piece mounting fixture. The aforementioned robot joint and velocity limitations due to tool design could be solved with this solution. Figure 4.1-3 shows the first strategy utilising a rotational auxiliary work piece fixture axis.

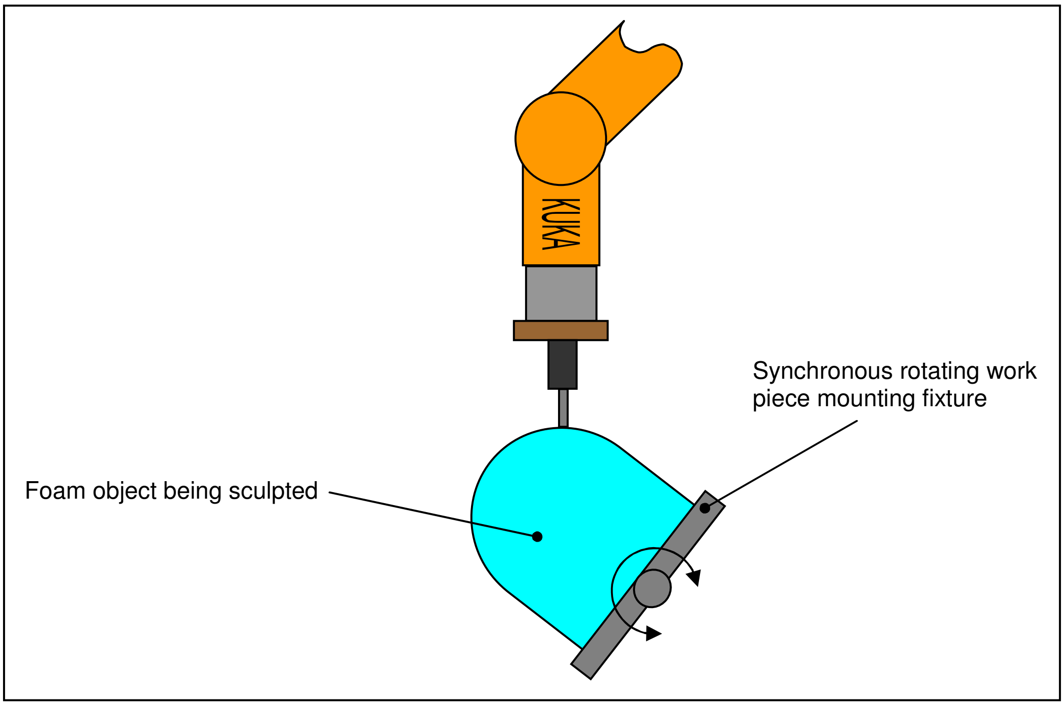

Figure 4.1-3 - Synchronous auxiliary rotational work piece fixture axis

It is recommended that work be undertaken to consider this strategy and its compatibility with the current robot and control system.

The second strategy would involve an auxiliary axis (either linear or rotational) which would manipulate the work piece incrementally one step at a time. For example, the work piece would be tilted at a fixed angle for a particular tool path. The work piece would then be tilted at another angle for the next tool path. This strategy would be ideal for the sculpting of prismatic type objects, and again would solve the aforementioned robot joint and velocity limitation problem. 5-axis tool paths would be applied to each side of the prismatic object. Figure 4.1-4 explains this strategy using a rotational auxiliary work piece fixture axis. The tool path is broken up into three parts; one for each side of the prismatic shape and is shown in red for each step.

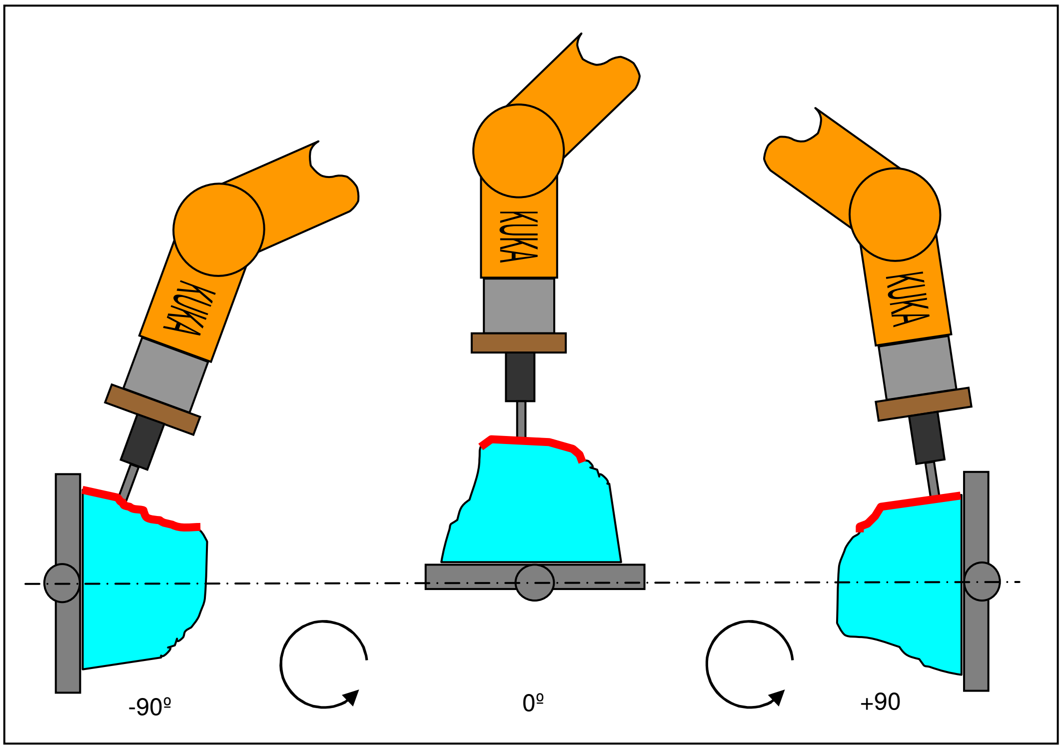

Figure 4.1-4 – Incremental auxiliary rotational work piece fixture axis

The area of work piece mounting and manipulation is extremely important and should account for a substantial portion of future work in developing the robotic foam sculpting system.

4.2 System Automation and Integration

The developed robotic foam sculpting system utilises seven separate software packages when sculpting a model which has been generated with the help of a 3D scanner. The software packages are:

- Polhemus FastScan software
- Matlab
- SolidWorks
- MasterCAM
- Microsoft Excel
- RobotWorks (add-in to SolidWorks)
- KUKA system software

Each of the software packages contribute to the overall functioning of the system. Currently, data is transferred between the packages in a rather un-automated fashion. For example, the transfer of the post processed and transformed tool path data to RobotWorks is achieved by manual selecting, copying and pasting. The system is disjointed and is not in a user friendly form. Consequently it is recommended that an area of future work be involved with integrating the required software packages and automating data transfer through the various steps of the process. This task may be difficult considering the types of software which need to be integrated. Several suggestions regarding the integration and automation of the complete robotic foam sculpting process are provided below.

- Automate data transfer between software packages.
- Investigate other software that can do the same job and is more compatible with the other packages. For example, SolidCAM which is another capable CAM package and also operates as an add-in to SolidWorks could be used to simplify the system further (this would result in the CAD model generation, tool path generation and optimisation and path simulation steps all being carried out within SolidWorks).
- Create a user interface to integrate the whole system.
- Provide a section in the user interface to control the path generation and optimisation step. Make this simple by only offering settings which are specific to foam sculpting as opposed to milling, drilling or routing. Hide all settings which are required but should not be altered by the user.
- Investigate the use of KUKASim. KUKASim is a package which performs complete offline KUKA robotics simulation. Once the programmed path has been created it can be simulated in a similar fashion to RobotWorks in terms of dynamic collision detection and the like. KUKASim is also capable of a full dynamic joint velocity and acceleration analysis and is completely compatible with the KUKA control software. This package could replace the cumbersome and unsuited RobotWorks provided a post processor could output the tool path directly to the native KUKA robot language from the CAM system.

4.3 CAD Model Generation

CAD model generation through a CAD system alone is trouble free and straightforward. On the other hand, it is more often the case that CAD models will be generated with the aid of a 3D scanner. As previously discussed, 3D scanners output their data in either the .TXT format or .STL format. This would not present a problem if MasterCAM could generate 5-axis tool paths on models represented in these formats. However, MasterCAM requires the model in the IGES format. Additionally, it is also important that the model be comprised of as few surfaces as possible (i.e. one continuous surface is better than several hundred knitted surfaces). The experimental work showed one method of re-creating an IGES surface from the .TXT format of the model data using a Matlab slicing algorithm which proved to be rather troublesome. Moreover, the procedure would not work for more complex models since the number of slices required to re-create the surface accurately would be far too high. .STL files can be converted to the IGES format in SolidWorks but every single triangular facet is converted into an individual IGES surface. There is not enough computing power to load this type of model into a CAM system let alone produce a 5-axis tool path on it!

In order to benefit from the use of versatile 3D scanners, the conversion of either .TXT or .STL model representations to continuous IGES surfaces is essential. The most capable software package available that can perform this conversion along with useful scanner data manipulation tools is ‘Geomagic Studio’. This package costs around $10,000 NZD. Geomagic also offer a package called ‘Geomagic Qualify’ which is capable of comparing scanner data from physical models with the original CAD model to test system accuracy and performance. This would be a future requirement if the confident sculpting of accurate models was to be realised. It is therefore recommended that an investigation be undertaken into the use and application of such software.

4.4 Tool Path Generation and Post Processing

The current system utilises MasterCAM to generate 5-axis tool paths on the CAD models to be sculpted. A modified 5-axis post processor then outputs the tool path data in five columns (x y z A B). This is then imported into a specially designed Excel spreadsheet which in turn performs further manipulations on the data including adding a constant valued 'C' column (since the robot requires six coordinates for every point on the path). The six column data from the spreadsheet is then imported into RobotWorks where the path is referenced, simulated and then converted to the native KUKA language. For all paths generated through this method, the KUKA language is simple and consists of a line of code for each point on the path. The line contains the six spatial and orientational coordinates of the point. An example of a typical line of code defining a point on a path is shown below:

LIN {X 50, Y -231.2, Z 546.2, A 35.90, B 90, C -21.65}

It should be noted that while the 'x', 'y' and 'z' coordinates will be the same as in the Excel spreadsheet (the values may differ due to translation of the path in the work space but will be the same relative to each other), the 'A', 'B' and 'C' coordinates will not be. This is because RobotWorks converts them to make them suitable for the KUKA robot which uses a different rotational order (this does not just change the order of the values but changes their values also) as explained in section 3.2. It would be possible to modify the MasterCAM post processor to output the actual KUKA native language provided the aforementioned rotation order conversion could be understood. This would comprise a beneficial portion of future work and would render RobotWorks redundant, granted the more suited KUKASim software could be used to perform the path checking and simulation. Alternatively an intermediate step would be to simply modify the MasterCAM post processor further to output x y z A B C along with the required transformations for direct import into RobotWorks, hence omitting the Excel spreadsheet step.

Another portion of required work in the post processing area is the need to write velocity commands for the robot within the code. This is especially important when utilising a uni-directional tool path which requires both the assignment of a cutting velocity and rapid return movement velocity. The KUKA language requires the velocity assignments to be entered prior to each movement type (i.e. define cutting velocity at the start of each pass and rapid return velocity at the end of each pass). This would require some knowledgeable modification of the MasterCAM post processor.

Currently 5-aixs tool paths are used for roughing passes. It is recommended that the generation of 3-aixs roughing tool paths be investigated in order to save time and effort. A 3-axis tool path is much simpler as it only contains the 'x', 'y' and 'z' coordinates. The rotational coordinates could just be set to constant values to suit the mounting of the work piece. The implementation of 3-axis tool paths would also highlight the need to investigate the use of tool tip compensation to avoid gouging. Gouging is when the corners of the tool cut into the surface deeper than desired. Tip compensation is also required for 5-axis tool paths but is less of a problem. MasterCAM has the capability to apply tip compensation, however, the nichrome bladed tool is somewhat different to conventional rotationally symmetrical milling and routing tools. Careful definition of the foam cutting tools with regard to cutting contact points is therefore required.

4.5 KUKA System Issues

The final recommended work lies in the area of the KUKA system and its compatibility with the rest of the process. Two main issues arose during the testing which should be addressed in future work. These are listed below.

- During the testing it was discovered that the KUKA system has a limit on the file size which can be loaded and executed. The limit corresponded to a tool path with around 2000 points. For an accurate path on a reasonably sized object (say 0.3 x 0.3 x 0.1 m) around 10,000 points are required. This obviously presents a problem. A common practice among robot programmers is to segment the file into several smaller files which are subsequently referenced from a parent file. The segmentation into a certain number of smaller files and the creation of a referencing parent file should be automated.
- Robot control files need to be created on the KUKA system. This is inconvenient since programming within this system is tedious and limited. This problem was negotiated by creating a template which could be filled in on another PC (where the rest of the process was carried out). A blank file was then created within the KUKA system with the same name as the one created on the outside PC. The prepared file was then transferred to the KUKA system PC via a 3.5" floppy disk (this is not ideal!). The blank file was simply replaced with the prepared one, hence fooling the system that the file was in fact created on the KUKA system PC. This process is obviously inconvenient and it is therefore recommended that alternatives to this be investigated.

These problems should have straightforward solutions; it is simply a matter of better understanding the KUKA system and how it operates.

5 CONCLUSIONS

This thesis began by presenting an overview of current conventional rapid prototyping systems. The overview showed that the main disadvantages of conventional rapid prototyping systems are the limited build size, long build times and high system and material cost. An extensive literature and technology review was then conducted on work which was similar to the novel system presented in this thesis. The literature provided many good ideas which could be applied. The 8-axis robotic rough cutting system developed by J Zhu et al was the most similar to the system developed in this work.

Two sections of experimental work were conducted. The first was aimed at simply proving the concept of robotically effected foam sculpting. A crude procedure was developed which proved to be rather tedious and manual, especially in terms of generating the tool path for the nichrome cutting tool to follow. Qualitative observations of the cut surfaces were used to change the testing conditions from test to test in order to explore the effects and discover the parameters which produced accurate and smooth sculpted surfaces. 12 tests were documented and proved that the sculpting of satisfactory surfaces would be achievable given the correct parameters.

The second section of experimental work involved developing the aforementioned crude procedure to make it more automated, especially in terms of the tool path generation and optimisation step. An innovative five step procedure was developed which if followed can produce accurately sculpted artefacts using CAD models of the artefacts as the primary process input. The five step procedure is summarised below:

1. CAD model generation – either from scratch in a CAD system or with the help of a 3D scanner
2. Tool path generation and optimisation through MasterCAM – 5-axis paths generated
3. Post processing of the output from MasterCAM to the required format
4. Simulation of the tool path and creation of the robot control code within RobotWorks
5. Setup and implementation

The innovative procedure was tested on two artefacts. The first comprised a simple surface created from scratch within a CAD system. The procedure proved effective and resulted in the successful sculpting of the artefact. The second artefact was a patient customised medical radiation therapy head and neck support. The CAD model for the support was created by scanning the back of the author's head and neck with a Polhemus FastScan 3D scanner. The head and neck support was successfully sculpted and fitted the author perfectly. The implementation of the procedure in the two tests highlighted several points including the speed in which the whole process can be carried out. The time taken from the scanning of the authors head and neck with the 3D scanner through to the physical sculpted artefact, was a mere 80 minutes; of which only 13 minutes was consumed in the actual setup and sculpting step! This is extremely quick when compared to conventional rapid prototyping systems (typically hours) and CNC milling.

Because the novel robotic foam sculpting system which has been developed is not perfect, several areas of future work were outlined. The areas included, tool and fixture design, automation and integration of the system procedure, tool pathing strategy for foam cutting and robot control system issues.

The work presented in this thesis will provide an excellent foundation for future development of the robotic foam sculpting system.

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APPENDIX A – SOFTWARE

This appendix contains the information sheets for the main software packages used throughout the work.

A.1 – SolidWorks

A.2 – MasterCAM

A.3 – RobotWorks

SolidWorks Software

3D CAD SOFTWARE FOR DESIGNING BETTER PRODUCTS

SolidWorks 3D CAD software is intuitive and enables you to develop better products by allowing your design team to work smarter and faster. Every release of the software delivers leadership innovations and hundreds of customer-requested enhancements, giving your organization a competitive edge.

Ease of use

Reduce design steps through dozens of timesaving innovations. Lessen visual clutter and minimize fatigue with Heads-up User Interaction, a set of intuitive display and control functions.

2D and 3D data integration

DWGeditor™ – Edit and maintain DWG files in their native format with DWGeditor, an editing tool that provides an interface familiar to AutoCAD® users.

Productivity enhancements – Take advantage of the best available tools for converting 2D data to 3D, revising 2D geometry, and enabling smooth adoption of 3D CAD technology, including extensive Help documentation for AutoCAD users.

Unique capabilities

SolidWorks Intelligent Feature Technology (SWIFT™) – Simplify the design process with the first technology that puts expert-level techniques for 3D CAD's most challenging design operations in the hands of every user. For example, SWIFT allows you to properly order part features such as drafts and fillets automatically.

Built-in part analysis – Confirm design integrity and lower cost of materials with COSMOSXpress, a point-and-click stress analysis wizard that lets anyone test part designs quickly and easily.

Design Communication – Share design concepts easily with eDrawings, the first email-enabled tool that dramatically eases product design communication. Simplify sharing of design concepts beyond engineering and manufacturing workgroups by circulating SolidWorks 3D designs as Adobe® PDF documents.

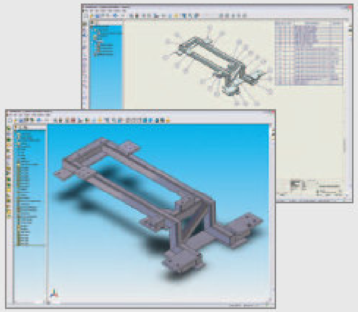
Machine design tools – Make use of a full set of weldment design, analysis, and documentation tools. Get best-in-class, fully associative sheet-metal capabilities that allow you to move rapidly from the design phase to final manufacturing drawings. Save time with a library of machine design features.

Mold design tools – Automate the creation of cores and cavities with built-in mold design tools. Use MoldflowXpress, a wizard-based design validation tool, for quickly and easily testing the manufacturability of plastic injection-molded parts.

Consumer product design tools – Speed design of consumer products with enhanced tools for creating and manipulating high grade surfaces easily.

Universal search capabilities – Quickly find all SolidWorks files, whether stored locally or on a shared network.

Online access to ready-made components – Save time with 3D ContentCentral, a web resource that provides CAD files for components from leading suppliers.



Improve machine design with built-in capabilities, including a full set of weldment design and documentation tools. ABOVE

Speed the design of consumer products with enhanced tools for manipulating surfaces easily and intuitively. RIGHT

Image of Handheld GPS System courtesy of Garmin International, Inc.

SolidWorks Software

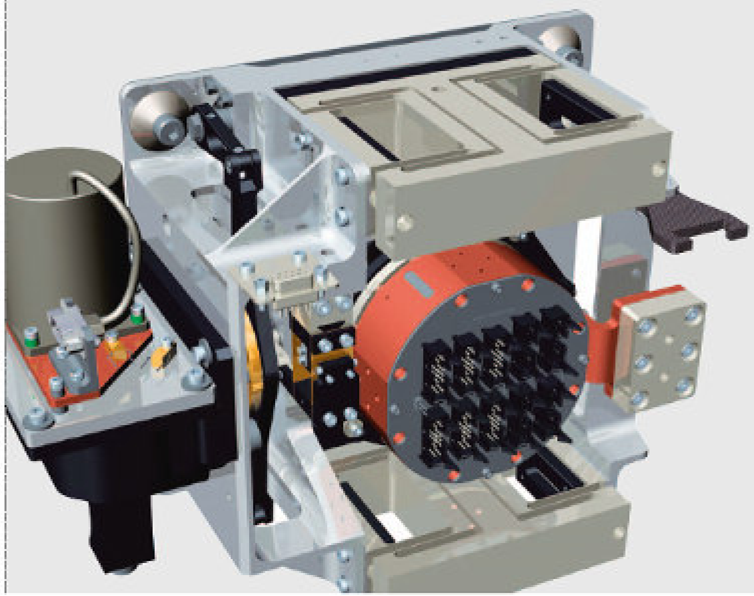
Best-in-class 3D CAD functions

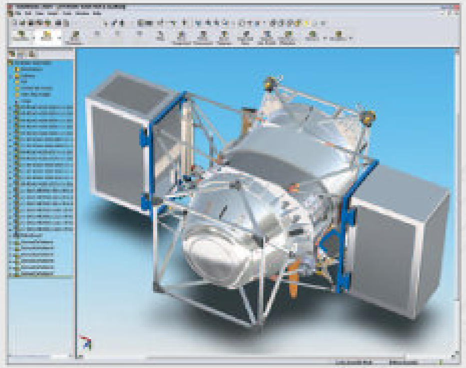
Part modeling – Create designs easily with extrudes, revolves, thin features, advanced shelling, area fill patterns, and holes using feature-based part modeling capabilities. Speed part modeling with feature-level control over multiple bodies. Make real-time design changes through dynamic editing of features and sketches.

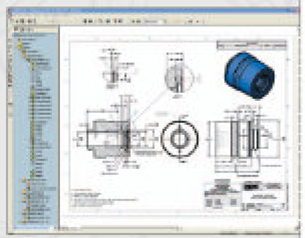
Assembly modeling – Reference other parts directly and maintain relationships when creating new parts. Gain unmatched performance for designing large assemblies with tens of thousands of parts. Work faster in Lightweight mode without sacrificing design and detailing capabilities. Drag and drop parts and features into place.

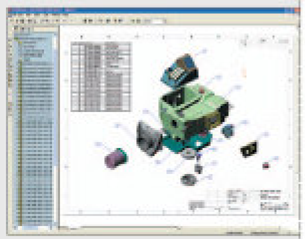
2D drawing – Develop production-ready engineering drawings without drawing a single line or arc. Construct fully associative drawings - drawing views and bills of materials update each time that you modify the part or assembly design. Automatically create multiple views with complete, accurate dimensions.

Surfacing – Capture and modify design intent with advanced 3D sketching capabilities. Use the Freeform surfacing tool to "push and pull" control points and easily create stylish, continuous surfaces. Generate complex surfaces using lofts and sweeps with guide curves, drag-handles for easy tangency control, and an innovative Fill feature. Trim, extend, fillet, and knit together surfaces intuitively.









Images at left and above courtesy of National Optical Astronomy Observatory, operated by the Association of Universities for Research in Astronomy, under cooperative agreement with the National Science Foundation

A.2 – MasterCAM

Mastercam X2 Mill – Fast. Flexible. Reliable.

A friendly familiarity
As you open Mastercam, there's an immediate comfort level with the look of the interface. Plus, we provide a set of training tools to help you get down to business creating toolpaths and cutting parts as quickly as possible. For instance, you can engage a learning mode designed for new users. And beyond the ease and comfort of the Mastercam interface is almost unlimited flexibility. You can customize its appearance and functionality. Even your keyboard and mouse shortcuts can be tailored to your preferences.

Do more with less clicks
We understand that saving programming time can get you cutting chips faster, boosting productivity and your company's bottom line. There are numerous programming efficiencies designed into Mastercam. Several functions are consolidated within a single option, streamlining the number of programmer interactions. Mastercam's smart Ribbon Bar appears only when needed, putting crucial tools at your fingertips at just the right moment.

Also with Mastercam, newly created geometry is "live". Simply adjust the attributes to the existing geometry and move on to the next task.

Toolpaths you can count on
At CNC Software, we have built our reputation for more than 20 years on creating the highest quality, most robust toolpath generation system in the world. The primary benefit that users continually cite about Mastercam is that they have complete command over all aspects of tool motion. Delivering comprehensive, clear tool control is crucial to programmers and one of many facets that sets us apart from the competition. With Mastercam X2, we have evolved our dominant toolpath system even further. It offers powerful toolpaths including new high speed cutting for any shop, advanced multiaxis features, and much more. It can also cut any type of CAD file, including mixed models comprised of any combination of wireframe, surface, or solid data.

Plays well with others
Mastercam can use virtually any CAD source file in the world including SolidWorks®, Solid Edge®, AutoCAD®, CATIA, Pro/E®, and many more. And even better, it tracks new versions of these files, recognizes changes and helps you update the toolpaths. In addition, Mastercam is designed with an open architecture, allowing specialists around the world to create unique add-ins tailored for specific needs.

Local experts, local support
Our company has the longest tenured Reseller channel in the business, which is a tremendous advantage for our customers. You have an exclusive Mastercam partner who is highly trained and experienced, ready to pass on his or her knowledge and to support you in every way possible. No other CAM software company has garnered such loyalty and strength. Our customers often remark about the significant role their Reseller has played in helping them achieve success and profitability with Mastercam.

The power of X!
The Mastercam X family of CAD/CAM takes another leap forward with Mastercam X2, bringing powerful new techniques and faster programming to your shop.

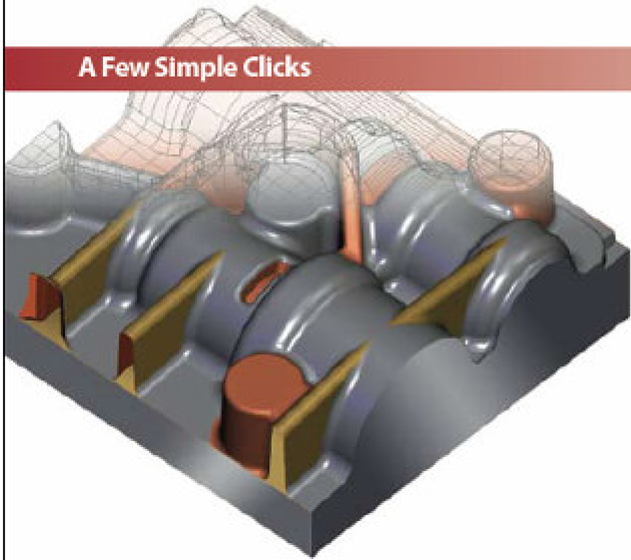
Mastercam X2.
CAD/CAM for the most important job – yours.

www.mastercam.com | 860.875.5006

Mastercam X2

CAD Functions

A Few Simple Clicks



"I am ecstatic about Mastercam. It makes programming a snap with so many shortcuts to create toolpaths. What I see on the screen is what I get on the machine. I give it a 10!"

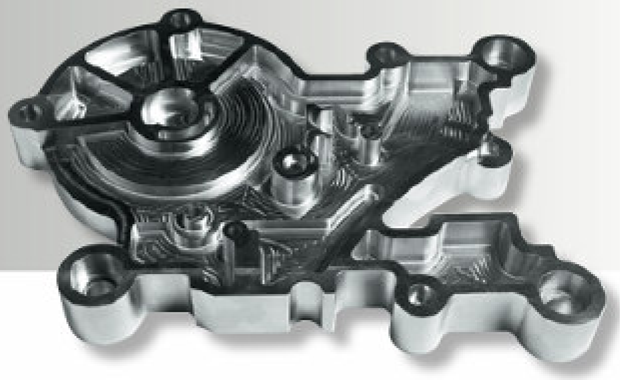
Richard Reyman, Owner
West Coast Cylinder Heads
Reseda, CA

www.mastercam.com | 860.875.5006

Powerful Part Modeling

Mastercam's streamlined CAD engine makes design work easier than ever before. Each piece of geometry you create is "live", letting you quickly modify it until it's exactly what you want. Further, with traditional functions consolidated into a few simple clicks, Mastercam simplifies the creation of even the most complex parts.

- Easy 2D and 3D geometry creation with complete wireframe and surface modeling.
- Fast creation of a wide range of NURBS and parametric surfaces, including powerful net and fence surfaces.
- New smart surface extension handles difficult surface intersections, delivering smooth, clean results.
- Flexible surface filleting offers constant radius fillets and point-and-click variable radius fillets.
- Remove trim boundaries and fill trimmed holes.
- Automatic parting line calculation for mold making.
- Associative dimensions update as you change your model.
- Extensive CAD editing tools, including unlimited Undo/Redo.
- User-definable drafting grid simplifies detailed construction.
- Customizable AutoCursor™ snaps to commonly used construction points.
- Solid modeling is available as an optional add-in.

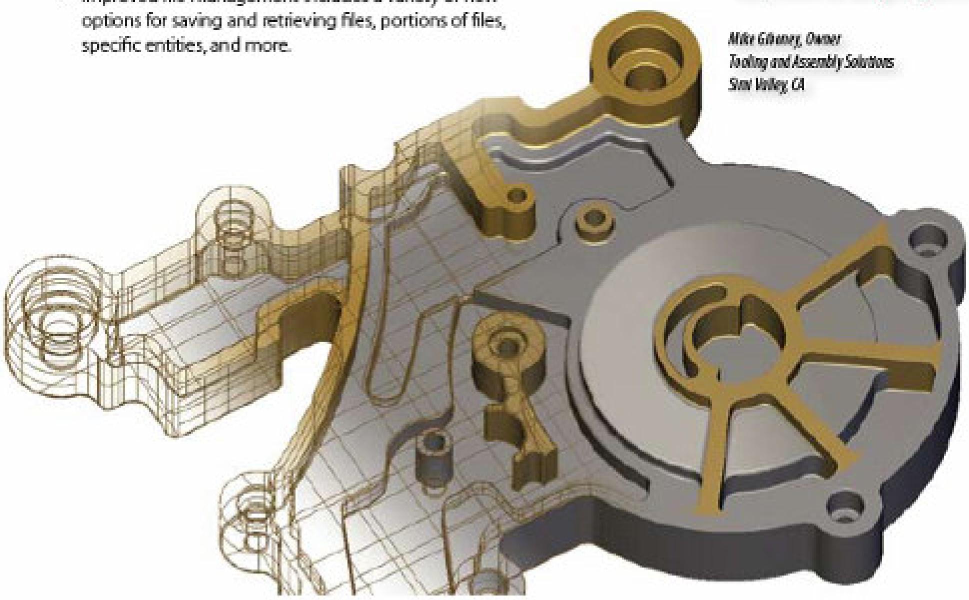


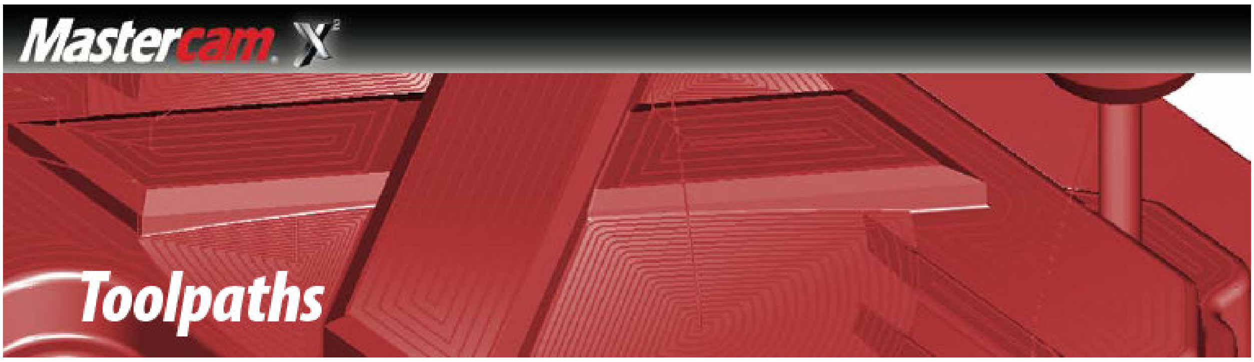
More Ways to Streamline Construction

- Analyze single points, between points, angles, and entire entities.
- Simplified and improved work coordinate system makes it easy to work on a model without having to move it in 3D space. Your new planes and origins are easily transferred to your G-code.
- Built-in data translators for IGES, Parasolid®, SAT (ACIS solids), AutoCAD® (DXF, DWG, and Inventor™ files), SolidWorks®, Solid Edge®, STEP, EPS, CADL, STL, VDA, and ASCII. Direct translators for CATIA®, Pro/E, and more are also available.
- Special no-charge Mastercam Direct add-ins put Mastercam in your SolidWorks, Solid Edge, or AutoCAD Inventor toolbars.
- Save a description with your part for record keeping.
- View thumbnail images of parts for easier browsing and loading.
- Improved file management includes a variety of new options for saving and retrieving files, portions of files, specific entities, and more.

"What I like about Mastercam is being able to make a program on the fly without having to spend hours ahead of time planning the job out. Mastercam gives us quick, error-free code that runs with ease, even on complex parts."

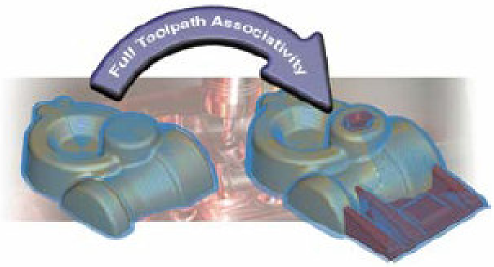
Mike Gibney, Owner
Tooling and Assembly Solutions
Simi Valley, CA



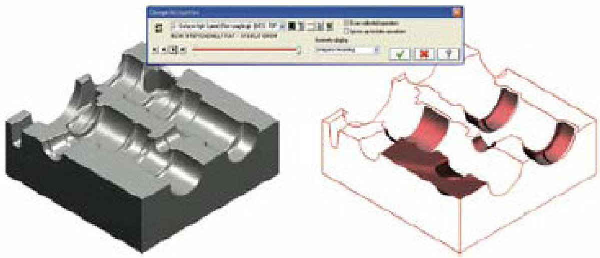


Capture Your Machining Knowledge

Mastercam's full associativity gives you the power to capture your work and build on your experience. Once you program a part – any part – you can modify any element of the job and immediately get updated toolpaths without starting over. Mastercam's intelligent NC programming lets you build a library of machining strategies done the way you want them. Just choose the saved operations, apply them to a part, and Mastercam adapts them to the new model. Fast, easy, and productive. The way programming should be.



CAD File Change Recognition & Toolpath Updating



Every shop faces engineering changes. Often, it can be difficult to track which file is the latest, what modifications have been made, and what programming changes are needed.

Mastercam X2 includes two powerful new tools – File Tracking and Change Recognition – that give you an easy way to identify these issues and streamline programming an updated file.

- Create a checklist of files to watch including Mastercam, SolidWorks, Autocad, or other CAD files. Mastercam alerts you when a newer version of any file on the list is available.
- Mastercam's Change Recognition identifies modifications to any type of CAD geometry with no file type limitations – any combination of wireframe, solids, or surfaces.
- Mastercam marks any toolpaths affected by the updated CAD file. You can quickly select the new geometry and update the toolpaths.
- Once you update an affected toolpath, automatically update any additional toolpaths that use that geometry.

The real power of these tools becomes clear when receiving engineering changes to a large file with multiple operations. Something as simple as a few additional drill holes could be frustrating to identify. Now, with a few mouse clicks, you can immediately locate and program these changes, saving valuable time.

Define Your Shop

Mastercam's Machine and Control Definition delivers a new way to make sure that your parts are done right the first time.

- Define features and characteristics for all the machines in your shop.
- Mastercam allows you to program only within the chosen machine's capabilities.
- Drag programmed toolpaths from one machine to another. Mastercam checks that they will run on the new machine, automatically making adjustments where possible.
- Mastercam tailors the interface to your selected machine's capabilities, and will even automatically load the toolbars that make you most efficient.

Efficient NC Tools and Toolpath Management

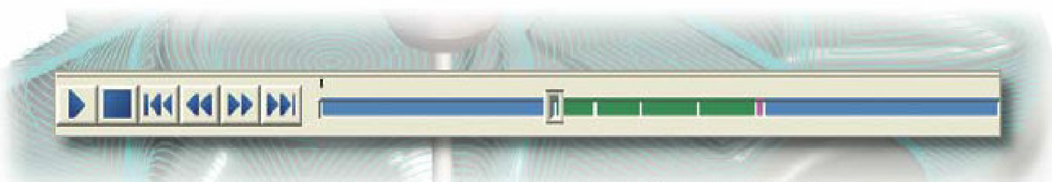
- Full control over tool approach and retract.
- Wrap a toolpath around a diameter with rotary axis substitution.
- "Safe zones" help ensure safe tool retract in all toolpath types.
- Significantly reduce the size of a program with toolpath filtering.
- Use all your tooling including lollipop, slot, dovetail, tapered, and much more.
- Automatically generate customizable setup sheets.
- Subroutine support.
- User-customizable tool and material libraries automatically calculate feeds and speeds.
- Mastercam's Toolpath Manager stores all your job's operations in one place. Quickly create, edit, and verify your toolpaths, or copy and paste parameters from one operation to another. Use machine groups to organize your operations, and easily copy and paste toolpaths and tool definitions from one machine group to another.

"The 3D surfacing toolpath capability in Mastercam is wonderful. I use it to get the fine detail I need and the part comes out pretty near polished. Our chromer loves it."

Jim Quinn, Programmer
Orange County Choppers
Montgomery, NY

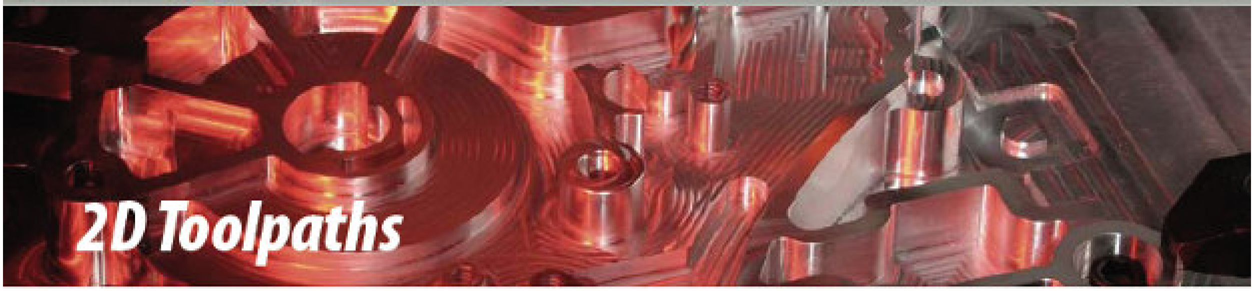
Dependable Toolpath Verification

- Watch and measure your part as it is cut from a solid block of material with Mastercam's solid model toolpath verification. The tool and holder are checked and displayed during simulation.
- "Play" the program with toolpath backplotting and get an estimate of machining time. Dynamically view all the vital information about tools and operations at any point, and even isolate specific areas to watch more closely.
- Quickly verify 2D toolpaths with a pixel paint of the full tool diameter to check the finish.



View your toolpaths with a quick color-coded slider bar that lets you view operations at any stage.

Mastercam X2



2D Toolpaths

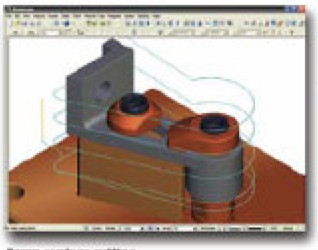
Contouring, Drilling, and Pocketing

2D machining ranges from the very simple to the very complex. Mastercam delivers all the tools you need for these operations.

- Pocketing styles include high speed, zigzag, one way, true spiral, constant overlap spiral, and "morph" pocketing, each with optional finish passes.
- Machine open pockets without creating additional geometry.
- Choose plunge, helical, or ramp entry.
- Special spiral pocketing options eliminate material when the tool turns a sharp corner.
- Contour and pocket remachining use a smaller tool to automatically clean out material left from previous operations.
- Wear compensation for contour and pocket finish passes lets you adjust for tool wear at the machine tool without creating a new toolpath.
- Choose multiple machining areas with a single selection.
- Click and drag a machining start point to anywhere on your model.
- Automated slot, circle, and thread milling.
- Choose separate taper angles for contours, pocket walls, and pocket islands, including islands of different heights.
- Smart pocket depth control for thin-walled pockets lets you machine depths without retracting, or machine all cuts in a single area before moving to the next.
- Facing cleans stock from the tops of islands or the entire part.

Contouring

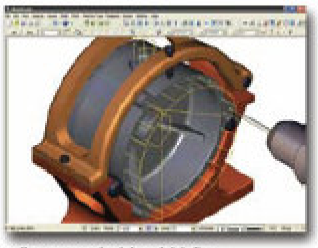
Automated contour remachining with a smaller tool.



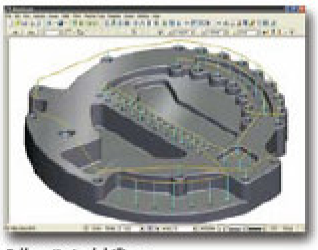
Ramp contour cutting.

3D contouring.

Drilling

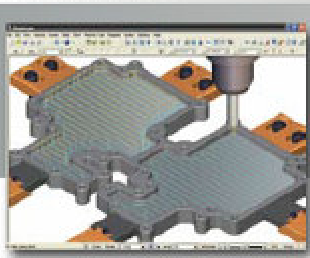


Fully automated solid model drilling.



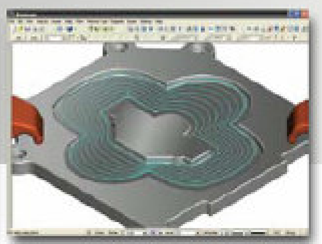
Fully optimized drilling.

Pocketing and More



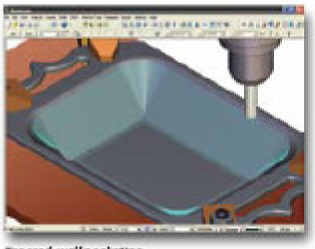
Fast zigzag and one-way pocketing.

Spiral pocketing.

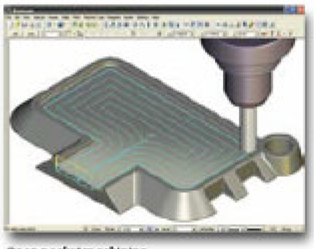


"Morph" pocketing cuts smoothly between two shapes.

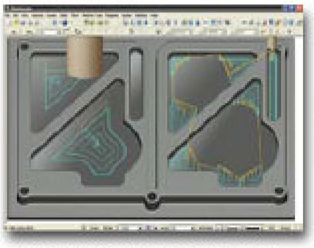
Automated circle milling.



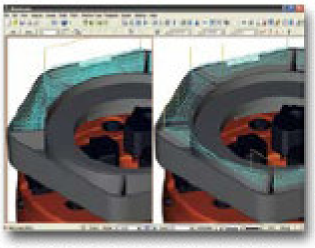
Tapered-wall pocketing.



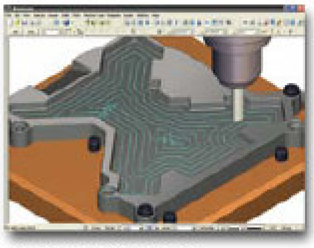
Open pocket machining.



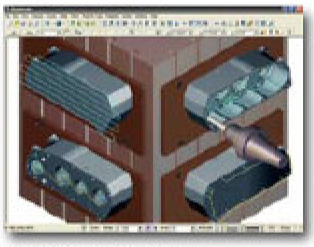
Automated pocket remachining with a smaller tool.



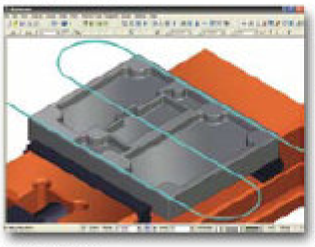
Complete your cutting pocket-by-pocket or by related Z-level cuts.



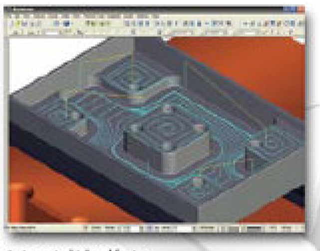
Specialized high speed pocketing.



Easy tombstone programming.



Quick part facing.



Automated island facing.

- Choose separate lead-in and lead-out for contours and pocket finish passes.
- Choose multiple roughing and finishing passes and multiple depth cuts for any contour.
- Easily machine 2D and 3D contours including parametric and NURBS splines.
- Automatically identify and pre-drill multiple operations at their plunge points.
- Automatic drilling countersink depth calculation.
- Optimize drill routines to minimize tool travel.
- Automatically create bolt circles or grids of points.
- Auto drilling creates complete cycles of drill operations on sets of holes, even with different diameters.
- With the addition of the Solids option, Mastercam automatically recognizes and programs drill holes on solid models, complete with pre-drill operations.

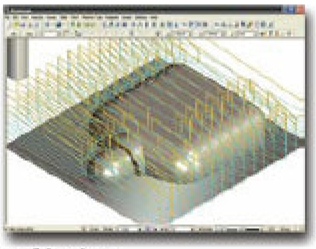
Roughing, Finishing, and Clean-up Machining

Powerful Roughing

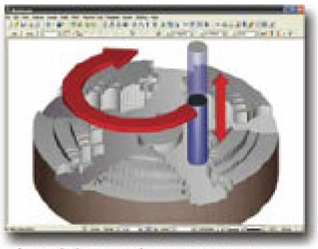
Fast, efficient bulk material removal is essential to efficient NC programming. Mastercam gives you a variety of techniques to rough machine all of your parts.

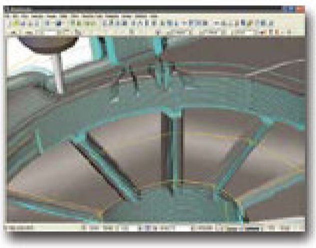
- Rough cut multiple surfaces, solid models, or a combination of both.
- Rough cut with constant Z contours or pockets.
- Rough cut by descending parallel or radial cuts, with complete control over plunging with positive and negative Z motion.
- Custom plunge roughing lets you rough straight from the top (with no XY motion) in any user-defined cut pattern.
- Constant Z rough restmill (remachining) identifies and machines areas that need to be roughed with a smaller tool.
- Automatic facing and critical depth recognition ensures flat surfaces that lie between Z-cuts won't be left with too much stock during rough machining.
- Automatically align all your roughing plunge points, making it easier to pre-drill those spots for production machining.

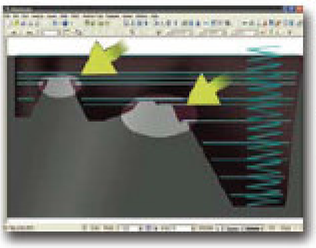
Roughing

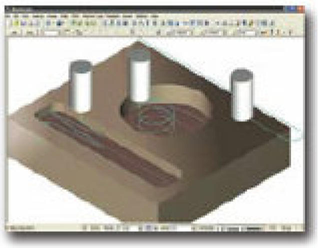

Parallel roughing.


Fast pocket roughing.


Advanced plunge roughing in any pattern.


Automated rough remachining with a smaller tool.


Automatic roughing of critical depths.

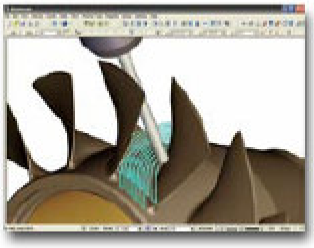

Multiple methods for smooth, efficient part entry.

Multiaxis Machining

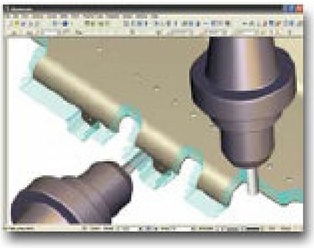
A Wide Range of Strategies

Multiaxis machining can dramatically increase a shop's competitiveness, and Mastercam offers a wide range of multiaxis machining strategies – both basic and advanced. With Mastercam, you have complete control over the three crucial elements of multiaxis machining: toolpath types, tool motion, and tool axis.

Toolpath Types

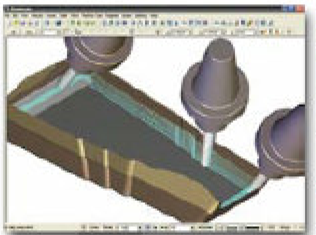


Efficient multiaxis roughing techniques help ensure accurate cuts and short turnaround times.

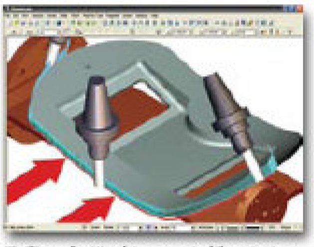


5-axis contour cutting for easy part trimming.

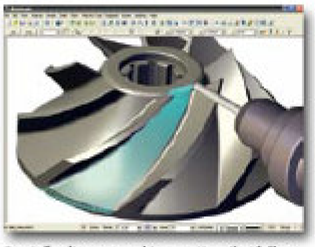
Fast, efficient 5-axis drilling.



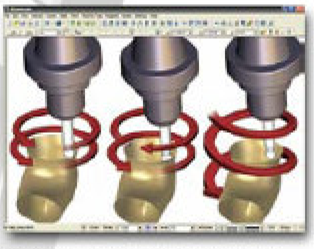
Multisurface swarf cutting keeps the tool edge against drive surfaces for a smooth finish.



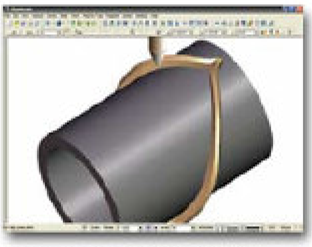
"Rail" swarf cutting lets you control the cut using a lower rail.



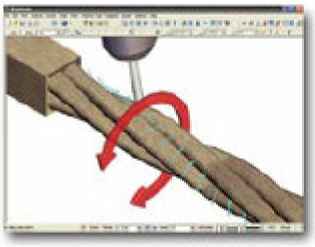
5-axis flowline can machine a pattern that follows the natural shape of the part.



Mastercam gives you a variety of tool motion choices: one way cutting, zigzag cutting, and smooth spiral cutting.

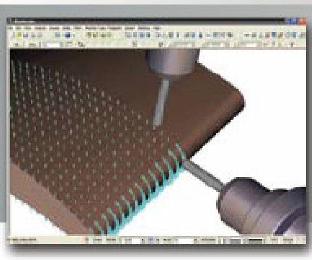


4-axis roll die programming delivers easy programming specialized for roll dies and vertical walls on cylindrical parts.

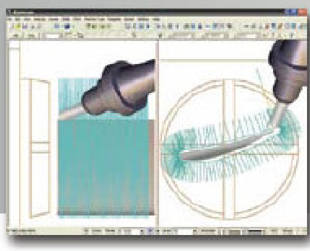


Streamlined rotary 4-axis cutting.

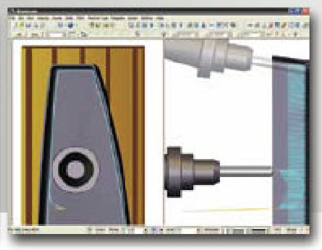
Tool Motion Control



Mastercam can add toolpath points to tightly curved areas for a smoother, more consistent finish.

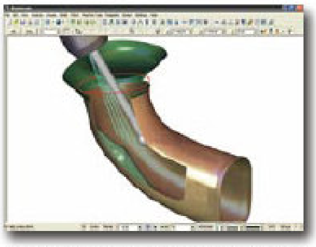


Mastercam gives you complete control over your lead / lag and side tilt.

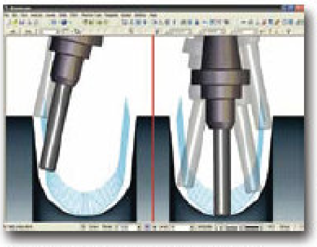


Full entry and exit control lets you determine exactly where and how the cutter enters and leaves your part.

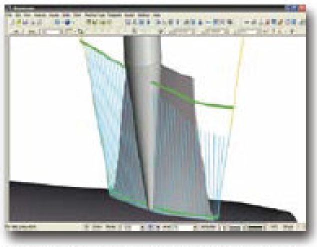
Tool Axis Control



Shank containment simplifies working in confined spaces.

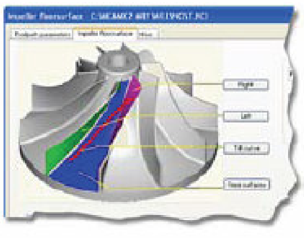


Mastercam's axis limits controls tool motion between defined angles, ensuring the tool tilt will not violate part or machine tool limits.

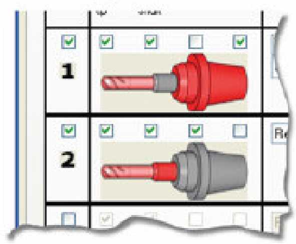


Quickly control your tool axis with a simple set of geometry chains.

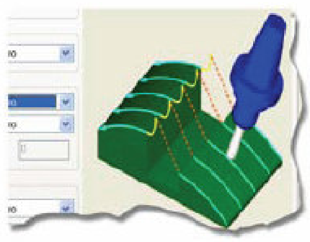
Clearly Illustrated Options



Mastercam's advanced multiaxis machining lets you choose what type of project you are doing and adjusts the interface to show exactly what you need.



Advanced gouge checking helps ensure safe cuts in even the most complex operations.



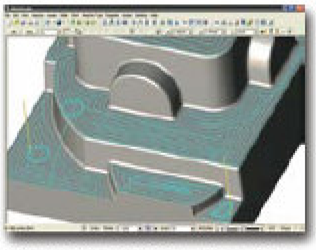
Mastercam's link options offer complete control over entry / exit, cut-to-cut, and between cut moves.

- Multisurface 5-axis roughing and finishing, including depth cuts, plunge roughing, and flowline machining.
- Machine 5-axis parts using spiral, zig zag, or one way tool motion.
- Swarf fanning and swarf machining over multisurface floors, plus "rail" swarf cutting for added control.
- Machine 5-axis curves with independent definitions of tool side angle and lead / lag angle.
- Create 5-axis contour toolpaths around surface edges for applications such as trimming vacuum-formed parts.
- Machine toward a single point for smooth tip cutting around an entire part.
- Easy 4-axis rotary axis and rolldie programming, and 5-axis drilling.
- Automatic point generator adds greater precision in difficult areas.
- Create full 5-axis motion from a 3-axis projected toolpath.
- Special options for machining cylinder heads and converting probe data to machinable geometry.
- Advanced gouge checking and a 5-axis "safe zone" around the part.
- Complete control over the tool axis, lead / lag, entry / exit, and tilt simplifies even the most difficult multiaxis jobs.
- 3D tool compensation in machine controls and full tapered tool support.

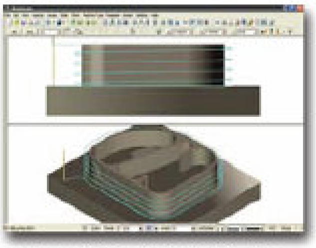
High Speed Machining

Faster Turnaround and Superior Finish

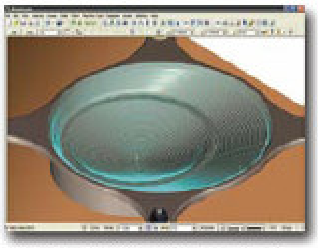
High Speed Machining is a powerful cutting method that combines high feed rates with high spindle speeds, specific tools, and specific tool motion. High Speed Machining can deliver faster turnaround and a superior finish. Mastercam includes a suite of High Speed Machining functions designed to help you make the most of this powerful technique, even if you don't have a high speed machine.



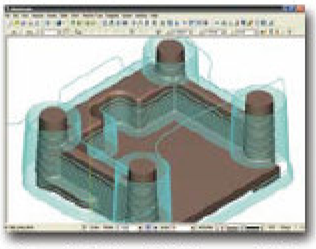
Automatically machine flat areas using new time-saving minimum retracts and smooth entry, exit and cut motion.



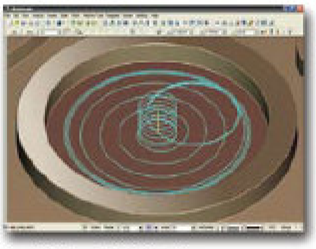
Contour parts with smooth, consistent ramping motion.



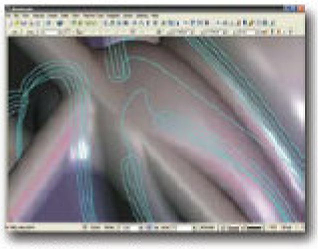
Projected spiral finishing delivers a smooth cut with consistent material contact.



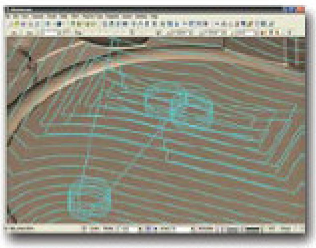
High speed waterline cutting delivers constant Z moves with smooth entries and exits.



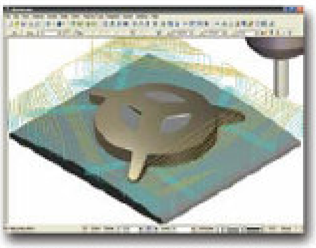
Smooth, automated circle milling.



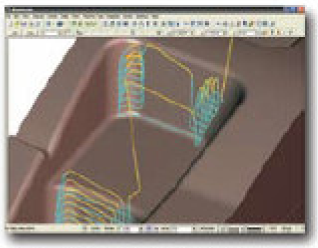
Specialized high speed pencil tracing removes material from a previous finish pass.



High speed area clearance removes bulk material from the inside out with smooth motion.



Smart core roughing cuts from the outside in. If it encounters a pocket, it automatically switches to inside out.



High speed rest roughing smoothly removes material left from a previous rough pass.

Intelligent Feed Rate Optimization

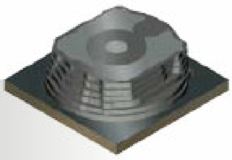
Save Time, Wear, and Money

Running an entire job at a single feed rate reduces efficiency. Running the same job at varying feed rates can save time, tool wear, and money. Our High Feed Machining function can optimize any 2-axis or 3-axis toolpath based on volume of material being removed and machine tool limitations to give you efficient, varied feed rates tailored to each job.

- Automatically vary feed rates based on volume. More material and the cutter moves slower; less material and the cutter moves faster.
- Automatically ease the tool into and out of corners.
- Create libraries of optimization settings for different jobs.

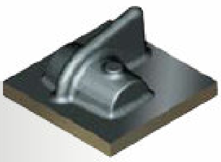
Pocket
Material: aluminum
Tools used: 1/2" flat end mill and 3/15" flat end mill

	No Optimization	With Optimization	% Saved
Time	2:11	1:48	**18.1%**



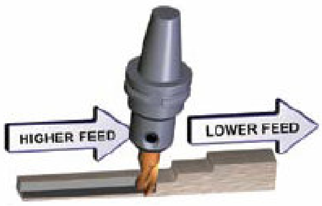
Multisurface Rough
Material: aluminum
Tool used: 1 1/4" flat end mill

	No Optimization	With Optimization	% Saved
Time	17:18	11:16	**34.9%**



Multisurface Finish
Material: aluminum
Tool used: .375 ball end mill

	No Optimization	With Optimization	% Saved
Time	2:36:44	1:53:51	**27.8%**



Constant Volume Removal
Mastercam slows the feed rate through deep material and speeds it up through more shallow stock.

Smart Cornering
Based on the part and machine tool characteristics, Mastercam adjusts the feed rate around corners and small radii for smooth transition in tight areas.

Mastercam X2

Specialized Options

Very often that little something extra – that one additional CAD or CAM tool – makes a specific job easier, faster, and more profitable. Mastercam offers a set of specialized add-in options for these occasions including:

- Automatic separation of surface model into core and cavity, including draft angle analysis and identification of problem surfaces.
- Bring in point data to create surfaces or STL data for reverse engineering and manufacturing.
- Sophisticated tools for traditional blueprint and CAD – based inspection.
- Automated complex shutoff and parting surface creation.
- Automated EDM electrode creation including a library of definable stock sizes and materials.

Other powerful CAD/CAM packages available from CNC Software:

Mastercam Lathe
Fast, flexible CNC turning

Mastercam Wire
2-axis and 4-axis wire EDM programming

Mastercam Router
Quick and easy router cutting

Mastercam Art
Turn flat line art into artistic 3D work

Mastercam Solids
Powerful Parasolid® based part modeling

Mastercam Mill	Level 1	Level 2	Level 3
CAD			
Complete customizability	x	x	x
Create and dimension live wireframe geometry	x	x	x
Read / write IGES, DXF, SAT, Parasolid, EPS & more	x	x	x
Read native AutoCAD, SolidWorks, Solid Edge & more	x	x	x
Read native CATIA and Pro/E files	Optional	Optional	Optional
Live surface modeling	x	x	x
Solid modeling	Optional	Optional	Optional
CAM			
Fully associative toolpaths	x	x	x
Automated feed rate optimization	x	x	x
Contouring, pocketing, and drilling	x	x	x
Automatic solid drilling when combined with Solids	x	x	x
3D contour cutting, trimming & remachining	x	x	x
On-screen toolpath verification	x	x	x
Safety zones for all toolpaths	x	x	x
Machine and control definition	x	x	x
Single and limited multisurface roughing		x	x
Single and limited multisurface finishing		x	x
Full multisurface and solid roughing			x
Full multisurface and solid finishing			x
Full multisurface and solid "cleanup" machining			x
Full multisurface and solid high speed machining			x
5-axis drilling and curve machining	Optional	Optional	Optional
Full 4-and 5-axis machining			Optional

System Requirements

- *Processor:* 32 bit, 1.5 GHz **minimum** Intel compatible processor (64 bit Intel compatible processors are supported).
- *Operating System:* Windows® XP, Windows® XP Pro 64 bit edition or Windows 2000 with latest service packs and updates.
- .NET 2.0 framework.
- *Memory:* 512 MB RAM, 1 GB available hard disk space.
- *Graphics Card:* 64 MB OpenGL-compatible (minimum).
- *Monitor:* 1024 x 768 resolution (minimum).
- *Mouse:* Windows® compatible mouse.

Mastercam
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RobotWorks

CAT - Computer Aided Teach-In

Situation

The use of robots is increasing by the day because they are very flexible and easily adaptable to different jobs. Deburring, polishing, gluing, dispensing, cutting, drilling and grinding are just a few examples of jobs which use robots today. Even some CNC-jobs can be done with a robot.

Robots are perfect for work with complex parts and they guarantee, even with a small series, increases in productivity. Still, often the use of robots fails because:

- The Teach-In with the robot and standard off-line program systems, especially with complex parts, are very expensive and labour intensive
- Standard off-line program systems are expensive and difficult to use
- The robot is not productive while it is being used for Teach-In
- Changes to the path are difficult and time consuming

Solution

RobotWorks is fully integrated into the 3D-CAD System SolidWorks, and quickly creates the desired path direct from 3D models. Using IGES, VDAFS, STEP and other built-in format it can import data from CAD systems like Inventor®, Unigraphics®, Pro/E®, CATIA® etc. Within minutes RobotWorks lets you know if the robot can reach all the path points collision-free. Only a few mouse clicks are needed to check alternative path solutions.

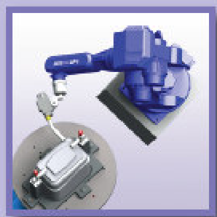
RobotWorks uses the user-selected faces and edges to create the points for the robot path. Saved tools and robot parameters let you easily define the environment and will help to create the path very quickly. The motion on screen shows the user when a path needs to be altered due to collision or reach problems. RobotWorks provides the user with handy tools to adjust and correct the path with only a few mouse clicks.

Because of the integration of RobotWorks into SolidWorks the robot path becomes part of the cell design. This way, any changes to the robot cell, i.e. collision, will immediately update the models and drawings – ready to be manufactured!

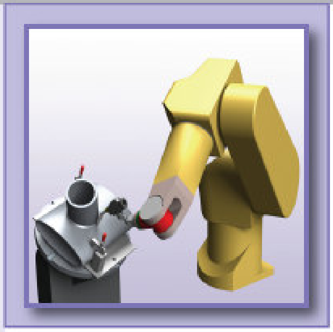
RobotWorks also can easily handle the tough job of moving parts. The more complex the part and path, the more benefit the user will get by using RobotWorks.

Tipp

RobotWorks is also very efficient for cases in which only a reach study is needed, or the cell layout and the position of the part to be manufactured has to be defined. Also, it's easy to decide which robot can do the job!



Applications



People in production only rely on success stories, not on theory! That's why we show you some examples:

Welding with a rotary table

Most kitchen refrigerators and air conditioners have a built-in compressor. One of the final steps of production is elaborated welding. This is used in order to enclose all the internal parts to form a hermetically sealed unit.

Not only do compressor housings have strange 3D shapes, but their welding must be continuous so that the sealing will be per-fect. This process calls for moving the part in space in a coordinated motion with the welding torch. However, programming robots to do this job is far from simple. A pro-gramming job like this may take many hours, even days!

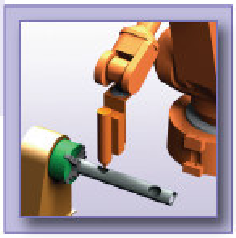
With RobotWorks first the path will be created in minutes following the geometry. Then the motion of the rotary table will be added and checked on screen to optimize the path. It needs only a few more mouse clicks to send the program to the robot – the whole Teach-In process takes less then 30 minutes.

Polishing of faucets

Because of the complex shapes and faces of faucets, in many cases they are polished by hand. This way of manufacturing is far too hard, noisy and dirty, so a robot may be considered. But to Teach-In the old fashioned way may take days and is very complicated, because the robot is to move the faucet along a fixed polishing brush.

RobotWorks will speed up that process dramatically and will make it simple too. The path will be sketched on the 3D model. While it is still a parametric path it may be changed and optimized in seconds. That's how complex shapes can now be handled by a robot.

Well known companies already have saved time and otherwise benefited using RobotWorks with applications for grinding tur-bine blades, deburring casting parts and planning complex robot cells.



Features of RobotWorks

- Supports most 6-axis robots
- Export of point data in many formats
- Writes direct programs for Fanuc, ABB, Kawasaki, ABB, Motoman, Kuka and Stäubli – with more to come
- Import of exitisting robot path possible
- Immediate calculation of reach and joint limits, immediate display of any problems
- Replacement of a robot in a cell with a mouse click
- Selection of the path by faces, edges and mid air points
- Teach-In through external digitizers like Microscribe and capturing hand motion directly
- User can define the motion parameter of the robot
- Moving part or moving tool
- Collision check
- Simple tools to support part calibration
- Motion in mid air is easy to define
- Any complex geometry can be selected as a path
- Interfaces to most CAD systems is included in SolidWorks
- Joint limits are checked, "close to" is shown
- Display of joint values at each path point
- Import of externally created path points
- Import of existing robot programs like SRC, LS, JBL, PRG (optional, restrictions may apply)
- Change of the path through offsets and soft transition like sine wave, linear etc.
- User can modify the path at any level
- Change of the robot cell or the position of the tool / part can be done very easy
- Path manager helps to get easy overlook over the path
- Addition of user defined events to every path point (laser on, close gripper etc...)
- Event editor included
- Easy to use and learn
- Very profitable investment – RobotWorks may pay off with the first Teach-In job
- RobotWorks is in English and comes with an outstanding help and tutorials.

Rotary table

For welding applications or pipe cutting, an add-on module is available which supports the use of a rotary table and two-axes positioner. RobotWorks makes sure that a perfect tool orientation and position is always kept. Also there are special features to cut contours in pipes. The module is made in such a way that every user can easily design his own rotary table or positioner and use it within RobotWorks.

Import of CNC data

RobotWorks is able to import 3-axis CNC programs and convert them into a real robot program. So a flexible and fast robot can replace a very expensive portal milling machine for the milling of plastic or wooden parts.

FanucWorks

Based on RobotWorks, FANUC created a special solution for their robots. This includes a real time connection to the robot and the ability to compare the real path of the robot to the one in FANUCWorks. So reality can be optimized offline and online!

CopyCAT

CopyCAT is an inexpensive measuring tool used to collect the hand motion of a master, while painting, deburring or other hand-driven applications. The collected path can transferred immediately to the robot. There is no faster way of Teach-In a robot.

Ask for detailed information.

APPENDIX B – MATLAB SLICING PROGRAM

Following is the specially created Matlab slicing program which was used to generate cross sections from data obtained from the 3D scanner. The program is commented throughout for explanation.

```
%Title: point_cloud_sectioner
%Author: Anton Posthuma
%Date: 28/02/07

%Purpose: Creates cross sections of objects represented by scanned point
%         cloud data. The sections can subsequently be imported to Solid
%         Works or a similar program to create a continuous lofted surface.

%Pre-conditions: The object to be sectioned must exist as x y z point cloud
%                data in a .txt file arranged in three columns in the
%                aforementioned order.
%                Each row should represent a single point.
%                The object must be oriented such that the
%                parallel sections are incremented in the x direction.
%                Furthermore, height variation must be in the z direction.
%                i.e. the cross section can be traversed pt to pt by
%                incrementing in the y direction.

%Input: The .txt file - insert file name below - A = load('filename.txt')
%       'incr' = the user specified spacing between cross sections measured
%       in mm. 'BW' = the user specified band width or sampling strip width
%      measured in mm. This is required since point cloud data is randomly
%      distributed. Do not use a BW > than 2.5 mm.

%Output: A structured array called 'CS(z).points' which containts a sorted
%        three column matrix for each of the 'z' cross sections. These can
%        subsequently be individually saved to text files.


clc;clear all

A = load('antonsneck2.txt');         %Insert file name here
x=A(:,1);                            %Extract column of x values
y=A(:,2);                            %Extract column of y values
z=A(:,3);                            %Extract column of z values

A=[x,y,z];                           %Compile matrix A with three columns

BW=0.5;                         %Input desired band width for sections here
incr=10;                        %Input spacing between sections here
B = size(A,1);                  %Counts the number of points in object

maximums=max(A);                     %vector of maximums [x,y,z]
minimums=min(A);                     %vector of minimums [x,y,z]
objectL=maximums(1)-minimums(1)      %length of object in x direction
numincr=round(objectL/incr);         %Calulates # of sections required

k=1;
for k=1:numincr;                          %loop for each cross section
xposition=minimums(1)+(incr*k)-incr;      %section x position

j = 1;
   for i = 1:B;           %loop for every point in object.
       if ((A(i,1) > xposition) & (A(i,1) < (xposition+BW)));
                          %Find out if the point lies within the band of
                          %width BW positioned at xposition
                          %If the point is within the band perform as below
            C(k).points(j,1) = xposition;    %write x position of slice
            C(k).points(j,2) = A(i,2);       %write y data pt.
            C(k).points(j,3) = A(i,3);       %write corresponding z data pt.
            j = j + 1;
       end
   end
```

```
end

%The following loop orders the points in order so they can be connected sequentially
%from one end of the cross section to the other. The starting point is the one with
%the lowest (y + z) value. The points are then ordered by finding the next closest
%data point.

for z = 1:k

    count1=size(C(z).points,1);
    yplusz = [];
    for m = 1:count1
        yplusz(m,1) = m;
        yplusz(m,2) = C(z).points(m,2)+C(z).points(m,3);
    end

    [val,rownum] = min(yplusz);
    point1 = C(z).points(rownum(2),:);
    C(z).points(rownum(2),:) = [];
    C(z).points;
    nextpt = point1;
    b = size(C(z).points,1);

    for p = 1:(count1-1)
        for n = 1:b
            dist(n,1) = n;
            dist(n,2)=sqrt(((nextpt(1)-C(z).points(n,1))^2)+((nextpt(2)-
C(z).points(n,2))^2)+((nextpt(3)-C(z).points(n,3))^2));
        end

        [val2,rownum2] = min(dist);
        if b == 1
            nextpt = C(z).points(1,:);
        else
            nextpt = C(z).points(rownum2(2),:);
            C(z).points(rownum2(2),:) = [];
            b = size(C(z).points,1);
            dist =[];
        end
        CS(z).points(p,:)=nextpt;
    end

CS(z).points = [point1;CS(z).points];

end
```